Root Development of Young Delicious Apple Trees as Affected by Soils and by Cultural Treatments

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SUMMARY

Young Delicious apple trees were grown in two soil types, clay loam and loess, in eastern Nebraska, under a variety of cultural conditions. The development of roots and tops was studied for the first three years after transplanting in the orchards. In all, 73 trees were excavated.

The first two years were about normal in precipitation at Lincoln (locale of the clay loam) while at Union (locale of the loess) there was a deficit of over 9 inches each year. The third year, 1934, was one of severe drouth and heat at both stations. The total rainfall deficiency for the three years was 30.8 inches at Union and 11.3 inches at Lincoln. The development of root systems was extremely rapid, the roots reaching a maximum depth of 8.8 and a lateral spread of 12 feet the first year, and 14.8 feet and 21.2 feet the second. During the third year the maximum lateral spread reached 29.4 feet and the maximum depth reached was 17 feet. This greatly exceeded the lateral spread of three-year-old tops, which was about 6 feet, and the height of the trees, which was 7 to 8 feet.

The root systems responded readily to changes in soil environment. Under clean culture a generalized root system was produced. The roots penetrated deeply and spread widely in such a manner that a very large volume of soil was thoroughly occupied. In competition with corn there was little lateral spread and most of the root growth was vertical. Under straw mulch the roots had a pronounced shallow, lateral development. Under sod mulch both tops and roots were dwarfed.

No change in the development of roots and tops could be attributed to the use of the fertilizers, ammonium sulphate and acid phosphate, except that the trees were injured somewhat by ammonium sulphate the first season.

Corn planted 7 feet from the trees had little effect upon tree-root development the first year, but when planted nearer to the tree row it resulted in dwarfing the root system. When planted 3.5 feet from the trees for two years, the average lateral spread of surface roots toward the corn was 8.4 feet, while below four feet in depth the roots were generally limited in spread to four feet. With corn planted 5 and 7 feet from the tree row, the average lateral spread of horizontal roots was 9.4 and 10.2 feet respectively. The average spread of roots of cultivated trees in loess soil was 15.5 feet after two years of growth.

The average spread of the roots of trees under cultivation in loess soil was 19.2 feet at the end of the third season. The most distinct difference between the root systems of trees under cultivation and those modified by competition with corn was the wide spread of roots of cultivated trees at great depths.

The trees in the mulched series at Lincoln all showed a marked lateral development of roots in contrast to those in loess soil at Union, but their vertical development was not so extensive. Cultivated trees after three years of growth had an average lateral root spread of 23.6 and 19.2 feet respectively at Lincoln and Union and an average root depth of 9.4 at Lincoln and 14.7 at Union.

There was a decided positive correlation between top growth and root growth for the trees in the mulched series in clay loam soil. Trees in loess soil did not show so distinct a correlation between top and root development.

Apple roots grew toward an adjacent optimum moisture supply. The response of the root systems to the various cultural treatments can be explained largely on the basis of the water content and its location in the soil. Straw mulch caused more water to be available in the upper two to three feet of soil. Here roots had a marked lateral development but vertical growth was less than under other treatments. Corn greatly reduced the soil moisture on each side of the tree row and tree roots turned downward as they approached this drier soil.

After three years of growth, apple trees on loess soil had absorbed about one-half the total available moisture present in the soil directly beneath the trees to a depth of 9 feet.

Root Development of Young Delicious Apple Trees as Affected by Soils and by Cultural Treatments

W. W. YOCUM [1]

The major problem of this investigation was to determine the effects of different cultural treatments and soil conditions upon the depth and lateral spread of the root systems of young Delicious apple trees during the first three years in the orchard. This study was conducted during the years 1932 to 1934 inclusive.

REVIEW OF LITERATURE

The literature closely related to this study is rather meager and indefinite. There is very little information concerning the depth and spread of roots of fruit trees, their rate of growth, or the effect of the several edaphic factors upon their development. There is, however, an abundance of literature more or less remotely related to this investigation. Most of the work on root systems of fruit trees has been incidental to other lines of research, such as the study of propagation and rootstocks, soil moisture, and cultural methods.

Research on the root systems of trees has been pursued chiefly in England, Russia, and the United States. At the East Malling Experiment Station, Kent, England, an extensive and detailed investigation of the rootstocks of fruit trees has been conducted since 1912. From this work has developed a study of the root system of orchard trees as they are influenced by various rootstocks and different soil environments. Most of this work has been done on bearing trees, 10 to 26 years old.

Rogers (29, 30, 31, 32) with his coworkers Hatton (13) and Vyvyan (34) have found that with apple rootstocks of the same genetic origin the direction of the main body of roots varied from tree to tree for no apparent cause. They found no evidence to support the common idea that the grafted and transplanted root system reflects the branching habit of the top in direction, spread, or depth. The growth of roots was greatly affected by soil texture, moisture, fertility, and aeration. In sandy soil the roots tended to be long, thin, and straight, and in loam stouter and more sinuous. Unmanured trees on sandy soil had relatively a more spreading type of root system than manured ones. The sparse, "hungry" type of root of the unmanured trees, they found, searches on and on through the poor soil for food. In a wet clay soil, 63.5 per cent (by weight) of the roots were found in a well aerated zone 50 to 100 centimeters deep.

Rogers (31) developed a unique method of observing root growth in the field and was able to determine when roots grow and their response to seasonal changes. A continuous moisture record was obtained by the use of the "dryness meter." Root growth in the field seemed to vary directly with soil temperature, provided sufficient soil moisture was present. Any deficiency in soil moisture was reflected quickly in decreased root growth, long before the leaves wilted.

Russian investigators have studied extensively the root systems of hardy fruit species on various soil types and under various climatic conditions. Their work is fundamental and was directed toward a better understanding of the nature and function of root growth and of the effect of soil moisture, fertility, temperature, oxygen, and physical structure upon root development. Kvarazkhelia (20) concluded that roots develop according to the law of limiting factors. Roots which developed in a location where one or more environmental factors were below the optimum, tended to make the greatest growth in the region of the most favorable environment, as regards moisture, fertility, temperature, oxygen, and porosity of soil.

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Kolesnikov (18) from a study of fruit-tree seedlings found that a definite seasonal order prevailed in the development of roots. In apples and pears during a growing season of five or six months, roots of eight orders were developed. The depth, length, and number of roots depended upon the variety, soil, and other environmental conditions.

Kolesnikov (19) also made a special study of the dying of rootlets of young fruit trees. Rootlets, he found, tended to lose their tips, following which more profuse branching occurred. The number of laterals per centimeter increased as the season progressed. Deep roots were often found to terminate in a number of rootlets twisted together. Several roots were often found tightly packed together following a straight course. The death of whole rootlets and even small subsystems occurred to a considerable extent over the whole main system, but more so near the primary root. Such denudation resulted in the steady march of the main absorbing portion of the root system into fresh layers of soil. This loss of rootlets was influenced by drouth and other climatic conditions.

Büsgen and Münch (7) offer an excellent résumé of the literature regarding root habits of forest trees. They concluded that the number, size, and direction of the root branches express, primarily, adaptations to the environment. The wealth of branching and the whole appearance of the root system is governed in a striking manner by the nature of the soil. In loose soil, roots are more plentiful than in compact soil. However, better nutrition may promote luxuriance in development of roots if there are no mechanical hindrances. The authors stated that "everything in this connection is not yet satisfactorily explained and the observations are not in complete agreement."

American investigators have studied tree root systems from many angles of approach. Comprehensive studies on underground plant parts in America are, however, scarcely two decades old. Most of these have resulted from the great impetus given root investigations by Weaver and his collaborators on grassland (44, 45), field crops (46), garden crops (47), and the bur oak (50). Baker (4) summarizes the findings of forestry workers thus: "The broader characteristics of root growth are inherited in trees and vary much with species. Root systems are typically plastic, however, and their ancestral form is often much modified to suit environmental conditions." Weaver and Kramer (50) state that "although the root habits of a tree are governed, first of all, by the hereditary growth characters of the species, they are often quite as much the product of environment."

Toumey (40) observed that "as a rule, roots of species adjusted to dry soils are extensive. The larger and more extensive is the root system, the greater the absorbing surface and the possibility of contact with remote water supplies." Again he said: "Although gravity causes roots to grow downward, water exerts even a greater influence, so roots grow downward into moist soil areas. Free water checks growth usually."

Holch (16), after a detailed study of five native species of deciduous tree seedlings in southeastern Nebraska, concluded: "The form of the root system seems to be correlated with the water content of the soil; the long tap root with strong branches is characteristic of species adapted to drier sites." He found that the depth and spread of root systems greatly exceeded the height and spread of tops. The maximum depths reached during the first year were: bur oak, 5.7 feet; shellbark hickory, 2.5 feet; red oak, 2.4 feet; linden, 1.2 feet; and black walnut, 4.5 feet.

Biswell (6) studied the effects of the environment upon the root habits of certain deciduous forest trees in central Missouri, and found that "Root systems of year-old trees were deeper and more branched in all cases where the seedlings grew in full insolation. . .The root systems of seedling honey locusts were 1.5 times as deep as the height of the top, and those of shellbark hickory 10 times as deep; other species were intermediate. Root penetration of all seedlings, except red oak, was greatest in loess soil, where depths of 36 to 65 inches were attained. Total lateral spread of seedling roots varied from 6 to 18 inches, except those of black walnut, which spread four feet in clay, three feet in alluvial soil, and 3.5 feet in loess."

Yeager (56) examined the root systems of certain trees and shrubs growing on prairie soils in eastern North Dakota. The depth and spread of the root systems were ascertained by trenching The larger roots were traced "until they became too small to follow." Approximately 97 per cent of the roots growing in Fargo clay were in

the upper four feet of soil. The deepest penetration of any roots—that of Hibernal apple —was 10.25 feet, and the slightest, that of butternut, was 2.7 feet. "It would appear," he concludes, "that tree roots occupy much the same soil layers as do ordinary field crops."

Marth (23) studied the root distribution of mature Stayman apple trees in Maryland. He examined the root development in the upper foot of soil outward from the tree trunk to a distance of 12 feet. The total growth of fibrous roots, per foot width of concentric area about the tree, apparently reached a maximum at six feet from the tree trunk in the lighter soils. In the heavier soils the maximum total fibrous root development was found at 9 to 12 feet, with some indication that many fibrous roots might be expected beyond this point.

Wahlenburg (43) tried to modify the root systems of western yellow pines in the nursery by fertilizing the soil at different depths. His results indicate the possibility, at least in perfectly controlled operations, of stimulating root development locally in any part of the root system by means of layers of rich soil.

Aldrich, Work, and Lewis (1) studied the concentration of roots of irrigated pears in relation to soil moisture extraction in the heavy clay soil in the Rogue River Valley, Oregon. They found a positive correlation between soil moisture extraction and the concentration of small visible roots. The most rapid moisture extraction by roots occurred two to eight feet from the trunk with mature trees. The greatest root concentration was at the trunk.

The effect of cultural practices upon the root development of apple trees has been clearly shown by studies by Cullinan (11) and Oskamp (26) in Indiana, and Beckenbach and Gourley (5) in Ohio. The trees studied were 4 to 40 years old and were growing under a variety of cultural conditions such as sod, grass mulch, straw mulch, cultivation, and cover cropping.

Sod produced the least growth of both top and root. Little difference was noted in the root distribution of trees grown under sod, cultivation, and cover crops. Oskamp found that while the root system under sod was similar in outline to that under cultivation, the spread was about one-third less, as was also the spread of the top. He also observed that there appeared to be more fibrous roots in proportion to the weight of the whole root system under sod treatment.

Roots under straw mulch differed little in maximum extent from those under clean cultivation, but were concentrated near the surface in most cases. Beckenbach and Gourley, in discussing the root systems of apple trees 40 years old, had this to say: "Where the mulch had been accumulating for 35 consecutive years, a solid mat of mulching material varying from three to six inches covered the soil. Throughout this mat . . . fibrous roots were so thick that a regular count could not be taken . . . With very few exceptions, these roots were all less than one millimeter in diameter." Beneath this mat of mulching material and roots, a network of larger roots, with diameters as great as forty millimeters, was found on top of the soil. Furthermore, as many roots were found in the soil horizons under the mulch as in the unmulched ones, or more.

Oskamp (26), however, found with four-year-old trees that straw mulch did not cause an increase of roots near the surface, and concluded that more than four years is required for young trees to respond to mulch in that section of New York.

A number of investigators have studied the growth response of fruit trees to the soil complex ramified by the roots. Veatch and Partridge (41) observed in Michigan that variations in the horizons cause differences in the distribution and extent of the roots in the soil. They believe that the distribution of the roots, laterally and vertically, is relatively unimportant, provided sufficient permanent supplies of moisture and nutrients are reached. If an abundant store of moisture and nutrients is close at hand, the roots need not penetrate so deeply nor extend so far as in soils lower in fertility and less able to furnish moisture continuously. The authors concluded that "the nature of the growth of the tree, so far as this is a factor of soil, is a function of a complex consisting of all the soil thickness through which the roots penetrate."

Partridge and Veatch (28) also made a more detailed study of the relationship between soil profile and root development of fruit trees. They observed from their study on a good sandy loam soil that the relative development of roots seemed to depend upon the permanence and uniformity of its moisture supply. The depth of root penetra-

tion, they concluded, was determined by tree age, the depth of available moisture, and by conditions in the upper soil which may favor or retard root development. The authors comment thus: "It is not thought that the relative importance of different portions of the root system can be evaluated entirely on a basis of quantity of roots alone."

The authors spoke of two sets of fibrous roots on the tree. The upper set was located in the surface soil, in which most of the organic matter was found and from which the tree obtained the major portion of its nitrogen and probably the greater part of its mineral salts. These upper roots probably supplied the greater part of the water used by the tree, when the surface soil was moist. The lower set of fibrous roots reached greater depths and if soil conditions were favorable they tapped a more permanent water supply. This reserve supply of water was important during periods of drouth. Of this portion of the root system the authors remark: "The number of these roots and their absorbing surface may be rather limited, but their capacity to supply the tree seems to be sufficient, provided they reach moist soil."

Anderson and Cheyney (3) concluded from their study of coniferous seedlings that the mechanical resistance of soils has more influence upon root development than has generally been accorded to it in the past.

Oskamp has made extensive studies of soils and soil moisture in relation to fruit growing. Oskamp and Batjer (27) concluded that the stand, yield, size, vigor, and rooting habit of Baldwin trees can be correlated with soil texture, percolation, and ground water. They found about sixty per cent of all roots of mature Baldwin trees in the surface sixteen inches but they state that deeper roots affect drouth resistance and production. The best soils for fruit growing were medium to light in texture with deep subsoils which permit rapid movement of water downward. Mature Baldwin trees varied much in depth of rooting, ranging from 2.5 to 8.5 feet in these areas, depending upon the character of the subsoil and substratum.

McClatchie (24) found, while studying winter irrigation of 6-year-old peach and apricot trees in Arizona, that roots extended vertically over 20 feet. Roots were most dense in the upper 6 feet and were fairly abundant 12 to 16 feet deep. His comment was that this root distribution makes possible the storage of water by winter irrigation for use in summer. He found that the total loss of water from the upper 25 feet of soil was 20 inches in one growing season; 80 per cent of the loss was during spring, 16 per cent during summer, and 4 per cent during autumn.

Schuster (35) has studied soil moisture and aeration in relation to the distribution of tree roots. He found that soil aeration is the most reliable test of effective soil depth. In nut orchards of Oregon he states that 85 to 95 per cent of the root system must be sufficiently deep or unsatisfactory results follow. Soils with only five to six per cent of air space at field capacity were very poorly aerated and contained few or no roots. Soils with ten to twelve per cent of pore space were satisfactory.

Stevenson (36) in a discussion of pore space observes that "Roots penetrate little beyond the zone of aeration." When pore space is all filled with water there are few or no roots. The result is a water-logged soil without a water table. He found that tree roots penetrate downward ten feet or more when soils wet to field capacity still have ten to twelve per cent or more of air space. Aeration, then, indicates the depth to which roots will penetrate and from which usable water may be extracted.

Sweet (38) from studies in the Ozark region, reported a very definite relation between subsoil conditions and the growth of apple trees. They penetrated deeper, grew larger, produced better, and lived longer where the trees found an open subsoil. He concludes that "Apple tree roots respond in a remarkable way to environment. They seem as sensitive to soil conditions as plants above ground are to heat and light."

From similar studies in western New York, Sweet (39) found that "soils and subsoils of nearly uniform color and with gradual gradations in texture are preferable to soils with abrupt changes in either color or texture." In the deepest, best-drained soils roots penetrated to a depth of 9 feet or more. In less perfectly drained soils rooting was about 6 feet deep, while in the most poorly drained soils the maximum depth of rooting was only three feet.

Veihmeyer, Hendrickson, and Conrad have done some fundamental work upon soil moisture problems in irrigated orchards in California. In regard to the wetting of soil, Hendrickson and Veihmeyer (14) state: "The addition of water brings soil to field capacity and wets only the amount that can be brought to this point." They find that

moisture may fluctuate widely without measurable results on growth and production of the tree, water being about equally available at all points from field capacity to the wilting coefficient. The use of water by prune trees was found nearly proportional to the length of twig growth. Veihmeyer (42) stated that "the use of moisture was not influenced by the supply, if above the wilting coefficient. Roots obtained water as readily, whether soil moisture was high or low, if it was above the wilting coefficient."

Conrad and Veihmeyer (10) pointed out that the capillary movement of soil moisture is too slow to meet the needs of growing plants, and that roots must extend into a body of soil to utilize its moisture. They state again that "optimum moisture conditions for growth may be taken to cover a range of soil moisture from the maximum field capacity to about the wilting coefficient." Lewis (21) reached the same conclusion in Oregon. He stated that plants suffer only when the zone of root penetration is outside these limits.

Hendrickson and Veihmeyer (15) reported that there is nearly constant use of water by trees during the winter. Soils wet six feet deep in the fall decreased in water constantly during the winter.

MATERIALS AND METHODS

One hundred twenty nursery apple trees of the Delicious variety were planted in the spring of 1932. They were selected very carefully from the stored stock of two large commercial nurseries, to obtain trees of uniform size and average top and root development. The trees were all two-year-olds, of 11/16-inch trunk diameter, and 5 to 6 feet in height. It was necessary to obtain trees which had roots developed equally well on all sides, in order that the trees might be equally affected on all sides by the various soil treatments. Trees grafted on seedling roots were decided upon for this investigation.

It may seem desirable to some to use only trees which are on their own roots in order to avoid the variable factors due to the presence of the graft union, and to the use of a heterogeneous lot of seedling roots in grafting. Swarbrick and Roberts (37) have shown, however, that when cions of one variety of apple are grafted, according to American methods, upon the roots of a heterogeneous lot of seedlings, very uniform root systems develop when the trees are grown under uniform conditions.

Trees were planted on April 15-16, 1932, at both Lincoln and Union. They were spaced ten feet apart and set at a maximum depth of eighteen inches. The tree roots were spread in approximately their normal position and the planting was done with care. The tops were then pruned back uniformly to a leader and one lateral branch located on the southwest side of the tree. No further pruning was given any of the trees during the second and third seasons.

At the University Fruit Farm, Union, Nebraska, trees were planted on fairly level ground near the bottom of a slope. Surface water, drained from the slope above, was diverted from this area after the first season. Trees or other deep-rooted crops had not grown on this land since it was cleared of virgin timber about 50 years before. Soil moisture was up to field capacity except near the surface where it had been reduced somewhat by annual crops.

Half of the trees were grown each year with corn as an interplanted crop, a very common practice in young orchards in this region. From

three to six rows of corn were grown on both sides of the tree row so that conditions were comparable to ordinary field conditions. The first corn row was 3.5 feet from the trees in some cases, in others 5 feet, and in still others 7 feet. These trees will hereafter be referred to as the Union corn series (Table 1).

TABLE 1.—*Cultural treatment of trees in the corn series preceding the time of excavation.*

Trees in treatment	Distance between tree and corn rows		
	First year	Second year	Third year
No.	*Ft.*	*Ft.*	*Ft.*
3	3.5	..	..
3	5	..	..
3	7	..	..
3	3.5	3.5	..
3	3.5	5	..
3	5	5	..
3	5	7	..
3	7	7	..
3	3.5	3.5	3.5
3	3.5	5	7
3	5	5	5
3	5	7	9
3	7	7	7
3	7	7	9
1	7	7	Cultivation

The corn was drilled in lister rows during the latter half of May. It was cultivated three or four times and the tree rows were kept free of weeds by hoeing. The variety of corn used in this investigation was Reid's Yellow Dent. This is a large, vigorous variety which has a total lateral spread of roots of about 7 to 8 feet and a root depth of 6 to 8 feet when mature. The corn made fair growth each season and was not noticeably stunted by competition with the apple trees.

The remaining trees in the loess soil at Union were cultivated during the three seasons. In some cases one-fourth pound of ammonium sulphate or treble superphosphate was mixed with soil in the bottom of the hole at transplanting time or in the surface six inches of the soil within a two-foot radius of the tree. Water was applied during the transplanting process in order to carry the fertilizer deeper into the soil. Notwithstanding these precautions some trees were injured by the nitrogen fertilizer. These fertilizers were also applied in the surface soil in early spring of the second and third growing seasons, in circles of five and seven foot radii respectively, at the rate of one-half pound per tree. These trees will hereafter be referred to as the Union fertilized series.

Trees at Lincoln were planted on fairly level ground near the bottom of a slope. A grove of trees had been cleared from this area about 20 years before. No deep-rooted crops had been grown there since and subsoil moisture was fully restored. The trees were divided into four main groups.

Some were grown for the three-year period under clean cultivation, others under straw mulch, still others under paper mulch, and a few under sod mulch. A portion of the trees were grown with half of their root systems under straw and half under cultivation, and still others were shifted from one treatment to another. This lot of trees will be known as the mulched series (Table 2).

Table 2.—*Cultural treatment of trees in the mulched series preceding the time of excavation.*

Number of trees in treatment	First year	Second year	Third year
3	Cultivation	....	....
3	Straw mulch	....	....
2	Paper mulch	....	....
2	Sod mulch	....	....
3	Half straw mulch, Half cultivated	....	....
3	Cultivation	Cultivation	....
1	Straw mulch	Cultivation	....
3	Straw mulch	Straw mulch	....
2	Paper mulch	Paper mulch	....
2	Sod mulch	Sod mulch	....
3	Half straw mulch, Half cultivation	Half straw mulch, Half cultivation	....
3	Cultivation	Cultivation	Cultivation
3	Straw mulch	Straw mulch	Straw mulch
1	Straw mulch	Straw mulch	Cultivation
1	Straw much	Cultivation	Cultivation
2	Paper mulch	Paper mulch	Paper mulch
2	Sod mulch	Sod mulch	Sod mulch
3	Half straw mulch, Half cultivation	Half straw mulch, Half cultivation	Half straw mulch, Half cultivation

Clean straw of the current year's wheat crop was used for mulching. After settling it was two to four inches thick, which was sufficient to smother all weeds. The straw was spread in a circle or semicircle with a radius of five feet the first season, seven feet the second, and ten feet the third.

The mulch paper was black, water-proof, unperforated, and impregnated with preservative material. It was three feet wide and had been manufactured especially for mulching purposes. The first season two strips were applied, one on each side of a row of trees. During the second and third growing seasons two strips of paper were applied on each side of the row. The paper was held in place by turning the edges into a shallow furrow and covering them with soil. This practice was fairly satisfactory for most of the season, but before the end of the growing season, the paper had rotted around the edges and also where water had stood on it after rains. It was then torn and whipped by the wind.

To form a sod, red clover was seeded with oats in the spring of 1932, just after the trees were planted. Annual grasses, weeds, and clover formed

the bulk of the cover of sod the second and third seasons. This sod was clipped two or three times annually.

Another lot of trees was grown under clean cultivation both at Lincoln and Union, so that comparisons could be made of the effects of the two soil types upon the development of the root systems. The space between the rows of trees was disked at frequent intervals and the soil kept free of weeds until August 1. After that date a light cover of weeds and grass was allowed to develop to protect the soil during the winter. Soil near the trees was hoed and kept clean throughout the season.

Soil samples for water-content determinations were taken at regular intervals, and certain other soil data were secured. Annual growth of twigs was measured to correlate with the growth of roots. During the fall and winter following each growing season, certain root systems were excavated, and their main features recorded by means of drawings.

The original plan of study called for the excavation of about one-third of the trees under each treatment after each of the three growing seasons. After the first and second seasons of growth, the trees were excavated as planned, but after the third the root systems were so extensive that only a much smaller number could be examined.

The direct or trench method of studying roots as described by Weaver (46) was employed. At the end of the first growing season 15 trees were excavated at Union and 11 at Lincoln. After the second growing season 19 trees were excavated at Union and 12 at Lincoln, and after the third season 9 at Union and 6 at Lincoln.

The entire root systems were removed from the soil the first year. A trench was dug about four feet from the tree to a depth of five or six feet. By picking into the side of the trench slowly and carefully the roots were discovered and excavated. When the tip of a root was located the root was tagged showing in inches the depth of the root tip and the lateral spread of the root as well as its direction from the trunk. After the roots of a tree had been thus uncovered and tagged, the tree was taken indoors and the roots were spread out in as nearly their natural position as is possible in one plane. The roots were pinned on wall board in their position as regards spread and depth, and drawings were made on cross-ruled paper, one square inch representing one square foot. One drawing was made from directly above, showing a horizontal view of the root system. A second drawing was made with the roots in a vertical plane, showing in all cases their distribution at right angles to the rows of trees. Thus the entire root system was portrayed.

The root systems had extended so far after two seasons' growth that it was not practical to excavate them completely. Instead, a trench was dug about two feet from the trunk and enough roots were exposed on the face of the trench to give a cross sectional view of the entire root system. Drawings of the root systems were then made with the roots in place in the trench wall. With this method, from one-fourth to one-third of the entire root system was excavated and drawn.

In all of the drawings only the main roots and their branches are shown. The finer details could not be included in drawings of such proportions, but the relative amount of branching in the various parts of the root system is indicated. The extreme depth and lateral spread of roots was accurately determined in all cases.

Lateral spread refers to the extent of horizontal roots from tip to tip, measured in a straight line along the surface. Roots usually take a meandering course, turning in various directions, but these curves and turns here were not measured. Likewise the depth of the root was measured in a straight line at right angles to the soil surface from the surface to the root tip, taking no account of the sinuous nature of roots. The natural course of the roots, however, is illustrated in the drawings so far as this is possible in one plane.

CLIMATE

The climate of eastern Nebraska is noted for its extremes of temperature, humidity, and precipitation. Records of the U. S. Weather Bureau show that the mean annual precipitation at Lincoln has been approximately 28 inches and its distribution of the Great Plains type. One to six drouth periods of 15 days or more occur annually as do also an average of 182 clear days. The long growing season in this mid-prairie region averages about 180 days without severe frost. The summer temperature ranges high, above 100 degrees occasionally from June to September inclusive. The average air temperature in summer is usually between 70 and 85 degrees and in winter between 20 and 40. Weaver and Himmel (49) in a 13-year study of the prairie environment of eastern Nebraska, give an excellent analysis of the climatic factors. They found that the average day humidity in summer varies between 50 and 80 per cent but frequently falls much lower. The average hourly wind velocity at Lincoln is about 10.7 miles, reaching a maximum of 13.2 miles in April and a minimum of 8.7 in August.

Climatic conditions were very extreme during the three-year period of this investigation. At the Union station especially there was great deficiency of rainfall during each year. The great drouth of 1934 was felt about equally at the two stations.

The year 1932 was normal in temperature variations but was somewhat below average in rainfall. At Lincoln rainfall was approximately normal, but at Union it was about 9.4 inches below. As there was no rainfall record for Union prior to 1932, comparisons were made with the record for Nebraska City, located 12 miles south of Union (Tables 3 and 4). Effective as well as total rainfall is indicated in the tables. According to Kiesselbach, Anderson, and Russel (17), rainfall must total 0.5 inch or more in two consecutive days if it is to be effective for crops in this region.

The year 1933 was marked by extreme weather conditions. Temperatures were high throughout most of the summer, and the winter temperatures of 1933-34 were also far above normal. Rainfall at both stations was nearly normal for July, August, and September; the trees made good

TABLE 3.—*Inches of rainfall at Union, Nebraska, during a three-year period compared with a 62-year average at Nebraska City.*

Month	Nebraska City[1]	Total rainfall, Union			Effective[2] rainfall, Union		
		1932	1933	1934	1932	1933	1934
Jan.	0.80	1.51	0.19	2.77	0.84	...	2.75
Feb.	1.14	1.16	0.36	0.99	0.76	...	0.50
March	1.48	0.48	2.88	0.97	...	2.44	...
April	2.72	0.14	1.75	...	...	1.75	...
May	4.45	1.52	1.15	0.35	0.83	0.52	...
June	4.63	5.04	2.71	3.43	4.87	2.71	2.40
July	3.91	2.72	2.38	0.53	2.32	2.38	0.53
Aug.	3.51	5.54	4.01	0.57	5.35	3.61	0.24
Sept.	4.04	1.71	3.69	4.30	1.20	3.69	3.73
Oct.	2.45	1.39	0.70	1.88	1.36	0.70	1.68
Nov.	1.28	...	0.04	3.28	...	...	2.30
Dec.	0.90	0.66	1.50	0.75	...	1.50	0.50
Annual	31.30	21.87	21.36	19.82	17.53	19.30	14.66
Departure from normal		-9.43	-9.94	-11.48	....	....	....

[1] Nebraska City is 12 miles south of the Union Fruit Farm. This record is from the U. S. D. A. Climatic Summary of the United States to 1930, Sect. 39. Column shows average total rainfall.
[2] Effective rainfall is considered to be a half inch or more in one day or two consecutive days.

TABLE 4.—*Precipitation in inches at Lincoln, Nebraska.*

Month	45-year average[1]	Total rainfall, Lincoln			Effective rainfall, Lincoln		
		1932	1933	1934	1932	1933	1934
Jan.	0.63	2.58	0.47	0.27	1.07	...	...
Feb.	0.94	0.95	0.25	1.09	0.80	...	0.65
March	1.22	1.06	3.03	0.60	...	2.45	...
April	2.51	1.61	1.22	0.32	1.12	1.20	...
May	4.04	3.08	1.68	0.40	2.97	0.54	...
June	4.24	4.91	2.26	2.33	2.73	2.15	1.24
July	3.86	5.90	5.91	0.36	5.54	5.79	...
Aug.	3.52	4.76	3.56	2.23	3.72	2.91	0.92
Sept.	2.91	1.75	5.34	4.00	1.08	5.01	1.72
Oct.	1.97	1.68	0.09	2.20	1.12	...	1.81
Nov.	1.15	0.05	0.82	2.42	...	0.50	1.16
Dec.	0.76	0.74	1.95	0.50	...	1.91	...
Annual	27.75	28.62	26.58	16.72	20.15	22.46	7.52
Departure from the average		+0.87	-1.17	-11.03	....	....	....

[1] From U. S. D. A. Climatic Summary of the United States to 1930, Sect. 39.

growth and the top soil was in favorable condition for root excavation. Rainfall was somewhat deficient, being 1.2 inches below the average at Lincoln and nearly 10 inches below at Union. The ground froze only slightly throughout the winter and excavation of the trees proceeded with little difficulty during every month except January, 1934.

The year 1934 was the hottest and next to the driest on record for the state up to that time. After a warm, dry winter there was practically no effective rainfall during March, April, and May at either Lincoln or Union. The trees started growth without the usual reserves of moisture in the upper two to four feet of soil. This fact may have caused an unusually rapid extension of the tree root systems into soil with a greater reserve of moisture. Rainfall during June of 1934 was about 50 per cent normal at Lincoln and 75 per cent at Union. Temperatures were very high. July was a month of uninterrupted heat and drouth; it was the hottest and driest July on record (see Weaver, Stoddart, and Noll, 51). The drouth continued unbroken until the last week in August. Thereafter rainfall was about normal at both stations. The deficiency of rainfall for the year 1934 was about 11 inches at both Lincoln and Union.

CHARACTERISTICS OF THE SOILS

The most profound changes in root development are in direct response to the soil environment (Weaver and Clements, 48). Temperature, humidity, and light, which affect root development through their effects upon food manufacture, water loss, and other activities of the shoot, are indirect factors as compared to the soil itself.

Profile and texture.—The soil in the University orchard at Lincoln is a fertile dark-brown type known as Waukesha clay loam. The upper layer of 18 to 24 inches (A horizon) is a fine-textured, friable, dark silt loam. This gradually grades into a dark clay subsoil of prismatic structure which lies between 24 and 36 inches of depth. This layer (B horizon) is the zone of concentration. It is very compact and sticky when wet, but shrinks and cracks badly when dry. Below three or three and one-half feet the subsoil gradually changes to a tan color and to a more mellow soil type, in many respects resembling loess. This C horizon extends downward many feet and beyond the greatest depth at which roots were found. It varies considerably in color and is marked with rusty streaks and numerous small calcareous flakes and concretions. The remains of old roots and root channels of former trees are everywhere. Numerous burrows of insects, earthworms, and larger animals also extend deeply, some to 10 or more feet. The roots of apple trees frequently followed these passageways in pentrating the deeper soil.

The Marshall silt loam at Union, Nebraska, is a fine-textured soil known commonly as loess. It is considered excellent for the growth of trees, since it is deep and porous. The upper 24 to 30 inches consists of a friable black loam of high fertility. Below 30 inches the soil gradually becomes lighter in color, reaching the typical tan color of loess usually in the fourth foot. Below this point the structure is very uniform. In some excavations a buried soil profile was encountered at a depth of 11 to 13 feet below the present surface.

Mechanical analyses of the two soil types show that they are very similar in texture in the upper six feet (12). Both are from 25 to 30 per cent clay in the surface foot and 35 to 40 per cent in the second. Clay content of the underlying parent material varies from 25 to 30 per cent.

Both soils contain 25 to 30 per cent of very fine sand, but less than 5 per cent fine sand. Only traces of coarser particles exist in these soils.

Rate of percolation.—In order to compare further the two soil environments and their influence upon the development of the root system, percolation studies were made to a depth of 6 feet in each soil type.

The percolation rate was determined from cores of soil six inches in depth and four inches in diameter. Brass cylinders with a cutting edge were forced into the soil with a jack to obtain the undisturbed cores. The soil was cut off smooth at each end of the cylinder and protected by filter paper, cheese cloth, and wire screen. A rubber collar was placed around the upper end. Water was applied slowly to the upper end of the soil column, and all surplus water was drawn off by suction, so that only a thin film was maintained on the surface of the soil during the determination. The water which percolated through the six-inch column of soil was measured in cubic centimeters per hour over a six-hour period and the average rate for the six hours was obtained (Table 5).

TABLE 5.—*Percolation rate, field capacity, volume weight, and hygroscopic coefficient of the Lincoln (Waukesha clay loam) and Union (Marshall silt loam) soils.*

Depth in inches	Av. percolation rate cc. per hour[1]			Field capacity, in percentage			Volume weight		
	Lincoln		Union	Lincoln		Union	Lincoln		Union
	Straw	*Cultivated*		*Straw*	*Cultivated*		*Straw*	*Cultivated*	
0-6	180	298	61	22.5	24.4	24.1	1.23	1.17	1.17
	98	269	..	...	24.8	25.2	...	1.08	1.23
6-12	0	110	198	23.2	24.6	23.7	1.22	1.37	1.25
	246	620	1308	24.1	26.8	25.7	1.33	1.16	1.29
12-18	198	383	481	23.9	26.8	27.2	1.30	1.33	1.25
	202	...	284	23.5	...	26.9	1.42	...	1.19
18-24	...	...	940	...	...	27.1	...	...	1.21
	...	...	1693	..	...	24.3	...	...	1.26
24-30	9	...	1532	21.9	...	25.2	1.48	...	1.32
	0	...	772	...	...	23.7	...	...	1.26
30-36	.	...	466	...	...	25.3	...	...	1.22
36-42	121	...	...	20.5	...	...	1.55	...	...
	6	...	...	24.3	...	...	1.29	...	...
48-54	17	...	103	23.0	...	23.6	1.28	...	1.33
	79	...	...	22.5	...	...	1.36	...	...
60-66	0	...	...	22.5	...	...	1.38	...	...
	3	...	...	19.4	...	...	1.41	...	...
66-72	.	...	337	...	...	23.1	...	...	1.27
	.	...	309	...	...	24.1	...	...	1.22

Hygroscopic coefficient at various depths[2]

Feet	1	2	3	4	5	6	7	8	9	10	12	15
Lincoln .	11.5	12.7	13.8	14.3	13.7	13.0	12.5	12.2	12.2	12.4		
Union ...	9.6	10.2	10.7	10.9	11.0	11.0	11.0	11.2	11.2	10.8	10.6	11.6

[1] Over a six-hour period.
[2] Method of Alway, Klein, and McDole (2).

Samples were obtained from each consecutive six-inch layer to a depth of 2.5 feet at Lincoln and 3.5 feet at Union. For the rest of the distance, at least one six-inch sample was obtained in each foot of soil to the sixth foot, inclusive. Duplicate samples were taken from the opposite ends of a trench ten feet long.

A study of the data on percolation shows that the rate is extremely variable, even with duplicate samples. Percolation through loess was more uniform and faster at all depths than through clay loam, showing that the loess is much more permeable. There was a slight zone of concentration in the loess to a depth of 12 to 18 inches. The clay loam soil had three distinct compact layers. The one in the first foot of soil may be due to the plow sole, the one in the third foot is the zone in which clay is concentrated, and the third layer of compaction in the sixth foot is doubtless due to heavy deposits of calcium.

The first sampling, which was made at Lincoln, was under a straw-mulched area to a depth of 6 feet. A second sampling was made under clean cultivation to a depth of 18 inches. The results show that percolation was much better under cultivation. Straw much had presumably changed the structure of the top soil.

Field capacity.—Field capacity is the amount of water which a given soil can hold against the pull of gravity, expressed as percentage of the dry weight of the soil. The field capacity was determined from the same soil samples which were used in the percolation study. The brass cylinders containing the saturated soil, still protected by cheese cloth at either end, were buried in dry soil for 48 hours (until the free water had time to be withdrawn by capillarity, and soil moisture to reach a stable condition) before weighing. The field capacity of the two soils seems about the same (Table 5).

Hygroscopic coefficient.—Hygroscopic coefficients were determined to a depth of 10 feet at Lincoln and to 15 feet at Union. They vary from 11.5 to 14.3 per cent in the Waukesha clay loam but only from 9.16 to 11.6 per cent in the Marshall silt loam (Table 5). The coefficients were determined by the standard method outlined by Alway, Klein, and McDole (2). Hygroscopic water is generally regarded as water which is unavailable to plants. Subtracting the hygroscopic coefficient from the total water content of the soil is a means of determining, approximately, the water available for plant use.

Volume weight.—Volume weight is the ratio between the weight of undisturbed soil and the weight of water which occupies a similar volume. This depends on the texture and compactness of the soil and the amount and condition of the organic matter present. Clays, clay loams, and silt loams range from 1.10 to 1.60 in volume weight, depending on structure. Sandy soils have heavier volume weights.

The volume weight of the loess soil was very uniform for the entire depth (six feet) sampled. It averaged 1.26. The clay loam soil at Lincoln, to a depth of six feet, averaged 1.35 and was much less uniform than the

loess. In the zone of concentration at 18 to 42 inches depth the volume weight was 1.48 (Table 5).

SOIL MOISTURE

Soil moisture is one of the most important edaphic factors affecting the growth of trees. In order to measure and evaluate this factor, soil samples for moisture determinations were taken six times during the growing season of 1932, twice in 1933, and 8 to 10 times in 1934. The data for the years 1932 and 1933 are presented in Tables 6 and 7, and those

TABLE 6.—*Available soil moisture at Union, Nebraska, during the seasons of 1932 and 1933.*

Depth in feet	1932					1933		Average moisture content
	June 14	June 30	Sept. 6	Oct. 11	Nov. 10	June 8	Sept. 27	
	Cultivated, uncropped field (control)							
1	16.9	13.6	13.4	11.2	18.7	11.2	18.1	14.7
2	17.4	15.6	15.0	14.4	16.3	14.4	16.5	15.7
3	16.3	14.1	14.3	14.0	14.2	14.7	15.2	14.6
	Under cultivated trees							
1	17.5	17.1	13.1	9.7	13.5	8.3	16.5	13.5
2	18.0	15.6	11.0	11.5	15.0	11.7	12.9	12.9
3	16.0	15.1	14.2	11.5	9.6	12.7	7.5	12.4
	Under trees with corn 3.5 feet distant							
1	16.9	13.4	12.9	10.8	15.7	10.7	18.3	13.1
2	17.2	14.9	10.8	12.9	20.2	13.5	16.5	15.1
3	16.5	15.6	14.0	10.7	13.8	14.6	7.3	13.2
	Under corn							
1	16.4	...	...	10.8	...	7.0	17.4	12.9
2	17.1	...	...	13.4	...	11.8	12.1	13.6
3	16.3	...	...	7.8	...	13.1	6.8	11.0

TABLE 7.—*Available soil moisture at Lincoln, Nebraska, during the seasons of 1932 and 1933*

Depth in feet	1932						1933		Average moisture content
	June 15	July 8	July 20	Sept. 7	Sept. 23	Nov. 3	June 7	June 27	
	Under straw-mulched trees								
1	20.6	19.8	17.0	20.7	24.3	19.7	19.5	13.6	17.7
2	14.1	13.8	13.3	16.2	19.6	15.3	19.9	14.3	15.8
	Under cultivated trees								
1	16.2	11.8	3.9	14.1	20.2	13.7	6.1	7.8	11.7
2	11.5	8.8	13.1	14.6	16.4	13.3	12.5	2.0	11.5
	Under paper-mulched trees								
1	14.8	12.3	10.6	4.4	7.6	13.2	10.4	7.8	10.1
2	12.1	12.2	11.6	9.0	10.5	...	11.7	11.5	11.2
	Under sod-mulched trees								
1	16.4	16.7	1.6	12.5	13.8	15.4	3.4	3.9	10.5
2	11.5	6.9	5.4	12.5	12.0	8.8	8.7	10.6	9.5

for 1934 in Tables 8 and 9. All soil-moisture data are presented as available moisture, that is, the amount of water held by the soil above the hygroscopic coefficient, expressed as percentage of the dry weight of the soil.

TABLE 8.—*Available soil moisture at Union, Nebraska, during the season of 1934.*

Depth in feet	May 6	June 9	June 28	July 10	July 26	Aug. 11	Aug. 24	Sept. 11	Sept. 19	Nov. 7	Av. for season
Middle of cultivated area											
1	12.4	13.5	11.8	12.4	6.1	9.6	7.2	14.8	12.0	18.7	11.8
2	14.3	13.5	12.6	12.9	9.4	11.7	10.0	13.7	12.4	16.1	12.7
3	13.2	13.4	13.0	13.0	11.7	12.6	11.4	12.0	12.2	12.7	12.5
4	12.0	...	11.8	...	...	...	...	...	...	11.2	11.7
5	11.6	...	11.5	...	...	...	...	...	...	11.3	11.5
6	11.3	...	11.3	...	...	...	...	...	...	11.6	11.4
Under cultivated tree											
1	12.2	12.5	15.3	9.5	5.9	5.4	−0.7	7.4	6.7	12.3	8.6
2	9.1	12.0	11.9	10.4	7.7	6.4	2.9	6.2	5.5	7.4	7.9
3	6.5	11.5	10.1	11.7	9.0	7.8	5.9	5.6	4.9	4.1	7.6
4	5.5	11.2	10.1	...	..	..	..	..	..	3.4	7.5
5	7.0	...	10.4	...	..	..	..	..	..	3.2	6.9
6	10.3	...	11.2	...	..	..	..	..	..	3.7	8.4
Under trees with corn 3.5 feet distant											
1	10.4	6.8	6.5	5.0	−1.2	1.2	0.3	5.4	2.7	9.3	4.6
2	11.5	5.7	6.1	5.9	1.8	3.0	2.6	5.4	2.4	6.3	5.1
3	12.2	6.8	5.7	6.8	5.7	4.7	4.4	6.0	3.9	4.6	6.1
4	12.0	8.7	6.9	..	..	..	..	..	..	5.6	8.3
5	11.3	..	8.4	..	..	..	..	..	..	7.3	9.0
6	10.8	..	8.7	..	..	..	..	..	..	8.5	9.3
Middle of eight rows of corn											
1	13.2	13.7	14.2	8.8	2.6	1.2	−1.1	7.9	6.1	18.2	8.5
2	13.5	14.2	13.7	10.8	4.4	2.2	1.1	5.4	4.3	17.1	8.7
3	13.1	12.3	11.3	6.5	5.8	3.7	2.7	3.9	3.4	16.1	7.8
4	11.9	9.4	8.9	..	..	..	..	..	..	14.0	11.0
5	10.7	..	8.9	..	..	..	..	..	..	8.7	9.4
6	9.9	..	11.4	..	..	..	..	..	..	7.4	9.6

Under straw mulch, soil moisture was considerably higher than under any other treatment at Lincoln during the first two years. The average amount of available moisture under straw was 16.7 per cent, under cultivation 11.6, under paper mulch 10.6, and under sod 10.0 per cent in the upper two feet of soil, for the time sampled during these two seasons.

In the corn series at Union the available moisture was about the same under all trees and corn alone, being 12.9, 13.8, and 12.5 per cent in the upper three feet of soil, while the cultivated uncropped area averaged 15.0 per cent during the time of sampling in 1932 and 1933.

A more complete record of soil moisture was obtained in 1934 (Tables 8 and 9). The reduction in soil moisture was more pronounced under all

TABLE 9.—*Available soil moisture at Lincoln during the growing season of 1934.*

Depth in feet	May 18	July 3	July 20	Aug. 3	Aug. 18	Aug. 30	Sept. 15	Sept. 28	Av. for season
				Under straw-mulched tree					
1	15.5	11.2	7.0	5.2	6.2	9.9	10.0	12.0	9.6
2	14.6	10.9	8.1	9.3	6.3	9.4	9.6	7.7	9.5
3	13.3	9.8	9.3	13.1	6.1	8.2	9.3	3.5	10.1
4	...	..	..	...	..	..	..	3.0	...
5	...	..	..	...	..	..	..	6.2	...
6	...	..	..	...	..	..	..	10.1	...
7	...	..	..	...	..	..	..	13.4	...
8	...	..	..	...	..	..	..	15.4	...
9	...	..	..	...	..	..	..	16.1	...
10	...	..	..	...	..	..	..	16.4	...
				Under cultivated tree					
1	11.2	6.3	3.9	11.6	5.3	4.7	6.2	6.1	6.9
2	16.4	7.8	5.6	12.0	6.5	5.0	5.8	5.4	8.1
3	21.0	8.8	6.5	11.2	6.5	4.4	4.6	6.0	8.6
4	...	..	..	...	..	..	..	6.1	..
5	...	..	..	...	..	..	..	6.6	..
6	...	..	..	...	..	..	..	8.8	..
7	...	..	..	...	..	..	..	11.1	..
8	...	..	..	...	..	..	.	13.0	..
9	...	..	..	...	..	..	..	14.6	..
10	...	..	..	...	..	..	..	15.8	..
				Under paper-mulched tree					
1	8.5	5.6	7.0	6.8	6.2	3.2	0.7	12.2	6.3
2	9.7	8.5	8.8	11.2	7.8	5.4	4.3	9.6	8.2
3	9.5	11.0	8.7	11.7	8.6	6.5	6.4	7.6	6.2
4	..	...	..	...	..	..	..	8.1	..
5	..	...	..	...	..	..	..	9.6	..
6	..	...	..	...	..	..	..	11.5	..
7	..	...	..	...	..	..	..	13.7	..
8	..	...	..	...	..	..	..	15.0	..
9	..	...	..	...	..	..	..	16.0	..
10	..	...	..	...	..	..	..	16.4	..
				Under sod-mulched tree					
1	7.4	7.6	−0.7	−2.1	1.7	5.4	2.7	9.8	4.0
2	12.3	10.7	2.3	0.2	2.7	5.0	1.7	7.0	5.2
3	11.2	11.7	5.0	2.4	3.9	5.1	1.4	6.9	5.9
4	...	...	..	..	..	..	..	8.2	..
5	...	...	..	..	..	..	..	9.4	..
6	...	...	..	..	..	..	..	11.2	..
7	...	...	..	..	..	..	..	13.4	..
8	...	...	..	..	..	..	..	15.0	..
9	...	...	..	..	..	..	..	16.0	..
10	...	...	..	..	..	..	..	16.4	..

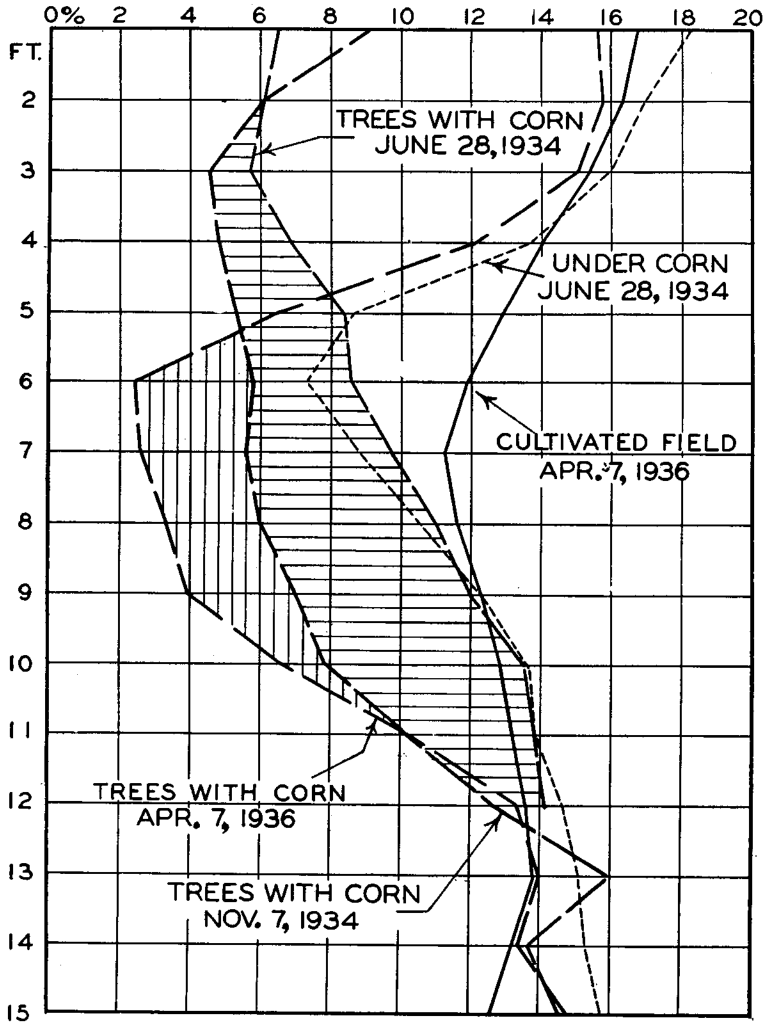

FIG. 1.—Available soil moisture at Union under trees intercropped with corn, after the second, third, and fourth growing seasons. The loss of soil moisture after two seasons is shown in the upper right unhatched area; loss the third season by the horizontal hatching; and the fourth season by the vertical hatching. In the cultivated check area soil moisture was fairly constant from year to year and near field capacity.

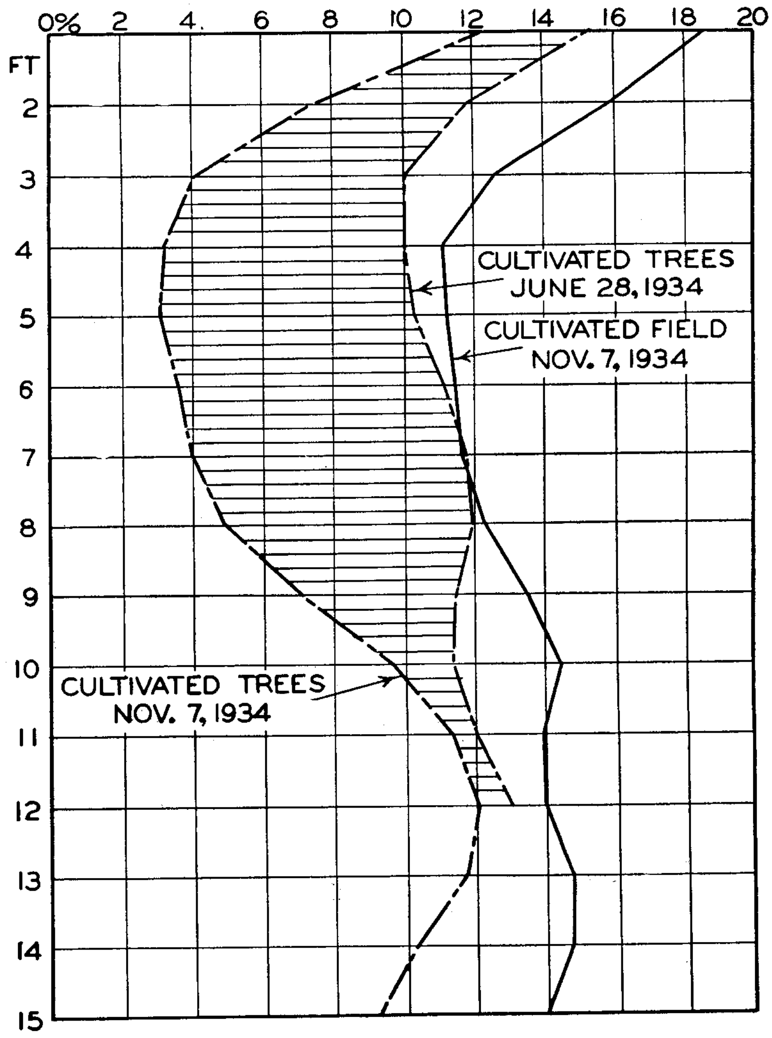

FIG. 2.—Available soil moisture at Union under cultivated trees before and after the third growing season. The hatched area indicates the great loss of soil moisture during this third season, a period of severe drouth.

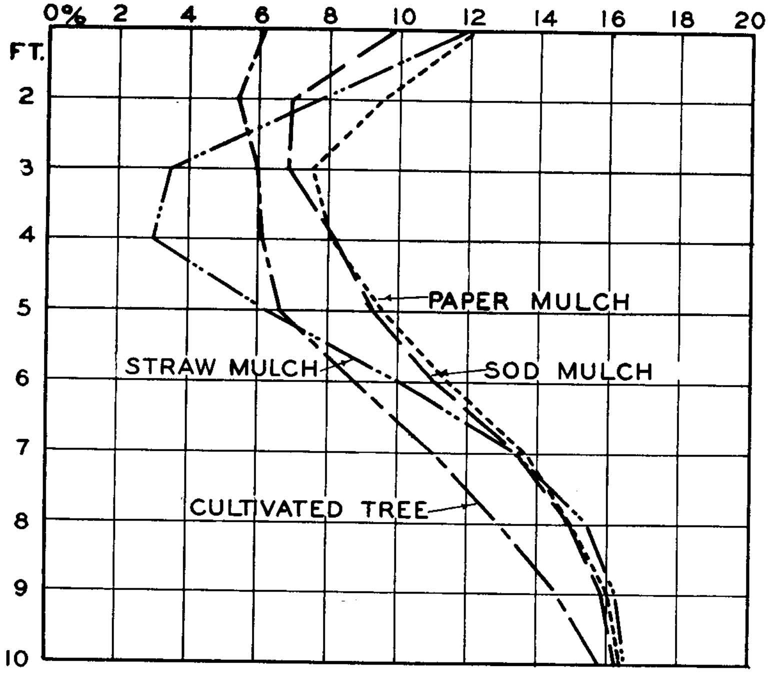

FIG. 3.—Available soil moisture under trees in the mulched series at Lincoln. September 28, 1934.

conditions during this season of severe drouth. In the mulched series the percentages of available moisture in the upper three feet of soil averaged 9.7, 7.9, 6.9, and 5.0 under straw-mulched, cultivated, paper-mulched, and sod-mulched trees respectively. The straw-mulched trees, however, had a marked development of roots in the upper soil and so extracted most of their moisture from this area. Magness (22) has shown that water absorption by apple trees is dependent upon root density.

The low moisture content under sod should account in part at least for the dwarfed condition of the root systems found there. The extremes of soil moisture under straw-mulched and sod-mulched trees showed a difference of 4.7 per cent in favor of the straw mulch. At Union available moisture in the upper three feet of soil averaged 12.3, 8.0, 5.3, and 8.3 per cent respectively in the cultivated uncropped area, under cultivated trees, under trees with close planting of corn, and under corn alone. In this third year the trees were drying out the soil faster than the corn. In the second three feet of loess soil the same condition seemed to exist, for soil moisture averaged 7.6, 8.9, and 10.0 respectively, under cultivated trees, trees with corn, and under corn.

The excavation of roots after the second year's growth revealed the fact that they had grown downward at a surprising rate and had reached

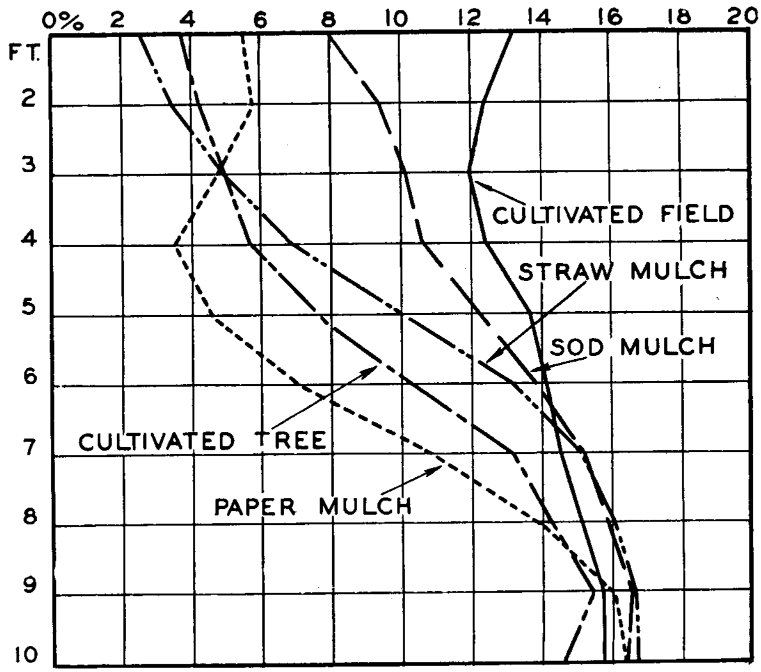

Fig. 4.—Available soil moisture under trees in the mulched series at Lincoln. June 22, 1936.

extreme depths. That fact seemed to indicate that soil moisture should be studied at greater depths. Accordingly soil samples were taken 12 and 15 feet deep, at Union, early in the third growing season, at the end of the third season, and again after the fourth growing season. Figure 1 shows that the change in available moisture under trees with corn was considerable to a depth of 12 feet during these seasons of deficient rainfall. Figure 2 shows the use of subsoil moisture under the tree that was cultivated to the end of the third growing season. These trees were well equipped with lateral roots in the upper 4 to 5 feet of soil, and since there was no other crop competing for moisture they seemed able to supply their needs for moisture near the surface during the first two years. During the third season, which was one of severe drouth, there was rapid use of subsoil moisture to a depth of 10 feet. In a zone from 3 to 8 feet in depth, 6 to 8 per cent of the available water was used during this one season, or about two-thirds of the moisture which was available at the beginning of the season. The trees intercropped with corn had dried out the soil to greater depths and to a greater degree than clean-cultivated trees.

At Lincoln the first deep soil-moisture samples were taken on September 28, 1934 (Fig. 3). The trees in the mulched series had dried out the clay

loam soil less than had occurred in the loess. No doubt the difference in rainfall during the three years accounts in part for this difference in the use of subsoil moisture. The total rainfall deficiency for the three years was 11.3 inches at Lincoln and 30.8 inches at Union.

Available soil moisture was again determined under the trees in the mulched series during June, 1936, after the fourth growing season (Fig. 4). None of the trees had reduced appreciably the moisture supply below 8 feet by this time. This indicated that root development was less concentrated below the 8-foot level. Above 8 feet the paper-mulched trees had reduced the available moisture most, having used two-thirds of it in the 6-foot level. The sod-mulched trees had reduced the soil moisture the least, but these trees had smaller tops than the others and less extensive root systems. The cultivated and straw-mulched trees had an intermediate supply of available soil moisture.

Wiggans (54), after observing the depth of rooting of young apple trees in this experiment, became interested in the subsoil moisture in orchards of various ages. His work has shown, as this investigation has indicated, that subsoil moisture is probably the chief limiting factor in the production and length of life of orchards in eastern Nebraska.

SOIL TEMPERATURE

Temperature is know to be a major factor in the growth of the tops of trees. Its effect upon the development of the root system is not so well understood. Whitten (53) of Missouri found in an investigation of transplanting that fall-planted apple trees usually begin new root formation about the first of January, after the surface soil has frozen.

It was found in this investigation, during the excavation of roots in early winter and early spring, that even freezing temperatures did not stop root growth entirely as long as the soil was thawing frequently. Normal uninjured white root tips were found near the surface in frozen soil and in soil which had been frozen a short time before.

Collison (9) found during the severe winter of 1933-34 at Geneva, New York, that apple roots continued to elongate almost continuously during January and early February at the 3.5 to 4.5 foot levels when the frost line had penetrated to a depth of 27 to 30 inches.

Recent work by Nightingale (25) and Rogers (31) indicates that temperature may play an important role in root growth of apple and peach trees. Their work seems to indicate that only a rather limited range of soil temperature is really favorable for root growth.

In this investigation no examination of root growth was made during the summer season but it is known that live roots were within six inches of the surface. Records of soil temperatures were secured in the mulch series during the daylight hours at intervals during the summer of 1933. During June and July the temperature six inches below the surface was from 2.5 to 5.5 degrees F. higher under paper mulch than under clean

cultivation (Fig. 5), maximum temperatures frequently reaching above 90° F. Temperatures under straw-mulch were 10 to 16 degrees lower than under clean cultivation in June and 8 to 13 degrees in July. These records agree with the findings of Werner (52) in his study of the effects of mulches on vegetables at Lincoln.

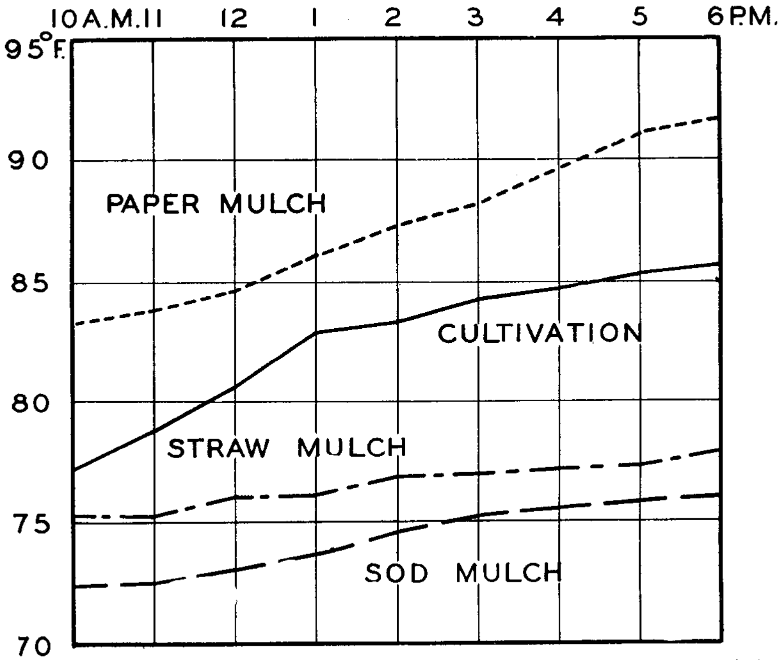

FIG. 5.—Soil temperature at six inches depth in the mulched series. July 12, 1933.

ROOT DEVELOPMENT AFTER ONE SEASON OF GROWTH

The development of the root system is considered to be the best measure of the response of the plant to the soil environment. In the drawings which follow are shown the horizontal and vertical views of the root systems of Delicious apple trees after one growing season. The tops are shown for comparison. The drawings were all made to scale after careful measurements, so they represent accurately the results obtained under the various soil treatments.

Results at Union.—Fifteen trees were excavated from the corn series at Union after one season of growth. In interpreting the results it should be kept in mind that competition was between an annual herb and a perennial woody plant. These plants started growth on a more or less equal basis. The corn roots developed more rapidly, however, and some grew outward to the center of the row of trees. This occurred even when the trees were seven feet distant. The tree roots continued growth very actively during

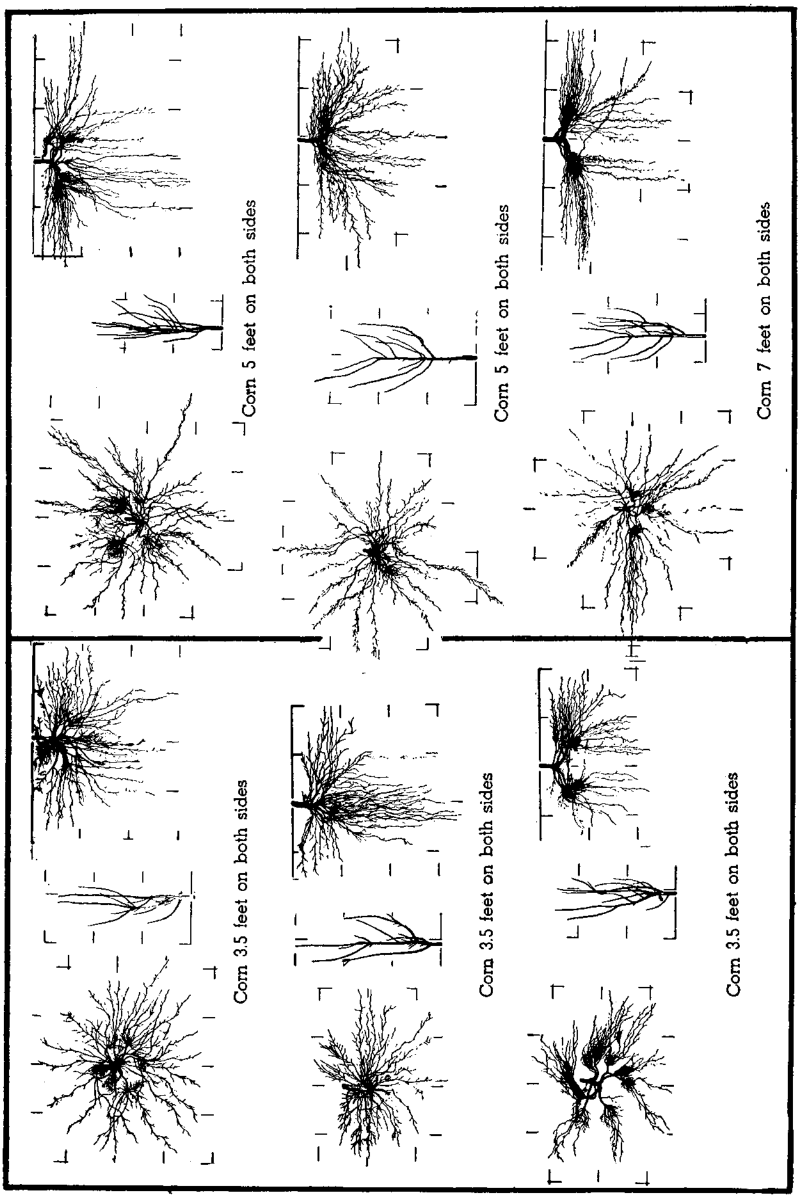

PLATE 1.—Horizontal and vertical views of root systems of Delicious apple trees one year after transplanting. These trees were grown on loess soil at Union. The tops are shown for comparison. Each interval indicates two feet.

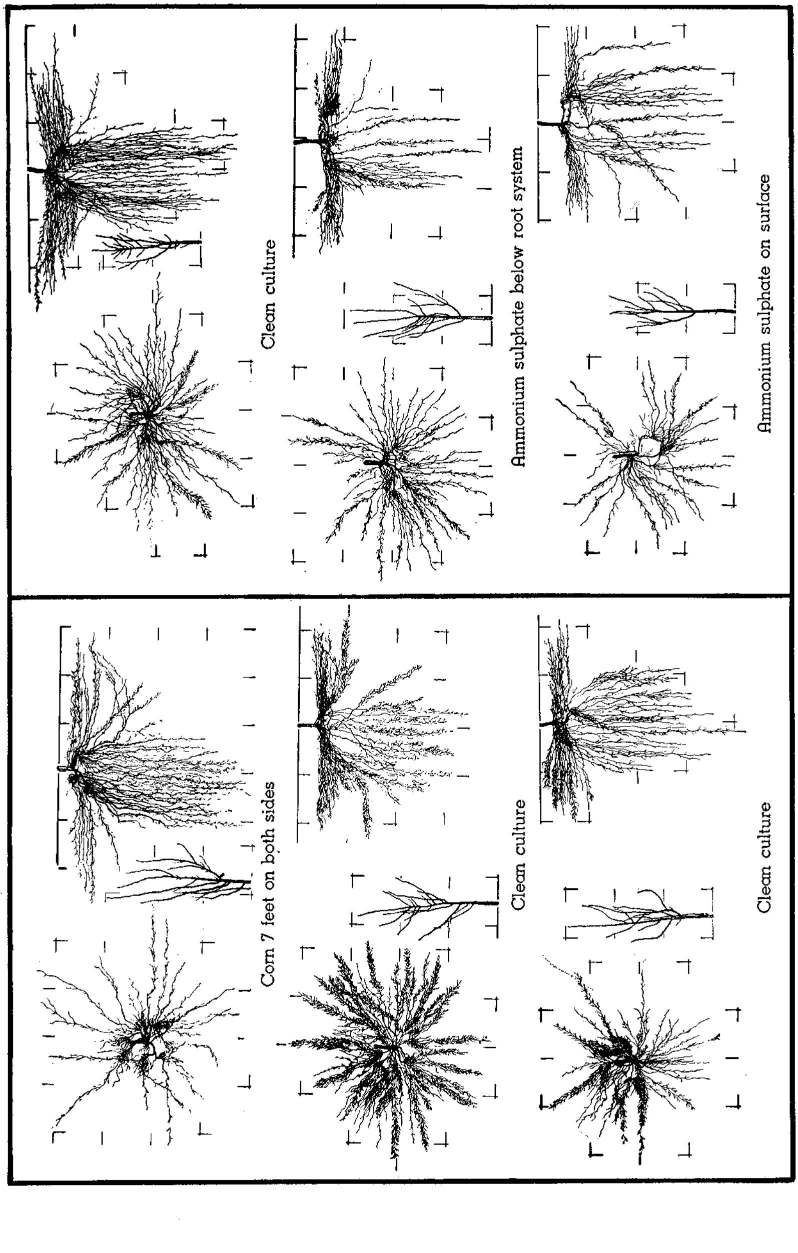

PLATE 2.—Root systems and tops of one-year-old Delicious apple trees grown on loess soil at Union under treatments indicated. Each interval indicates two feet.

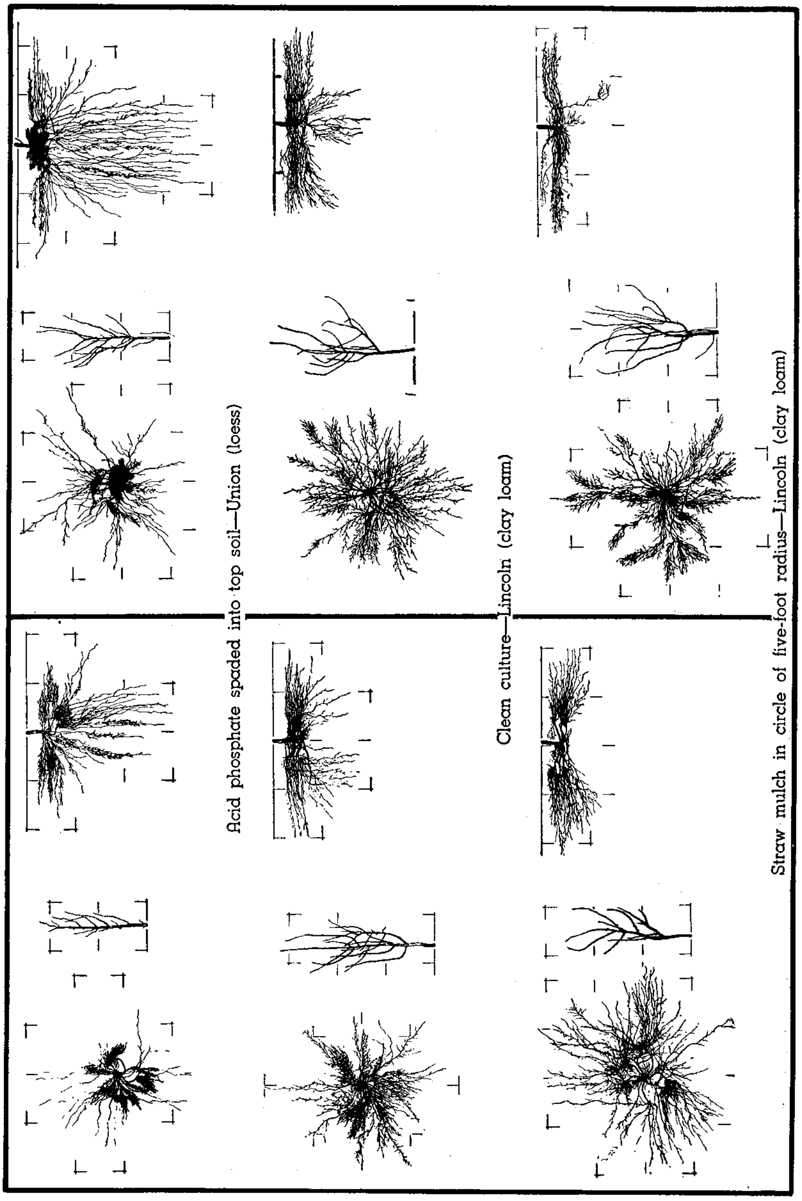

PLATE 3.—One-year-old apple root systems and tops. Two upper trees at Union (loess); four lower trees at Lincoln (clay loam). Each interval indicates two feet.

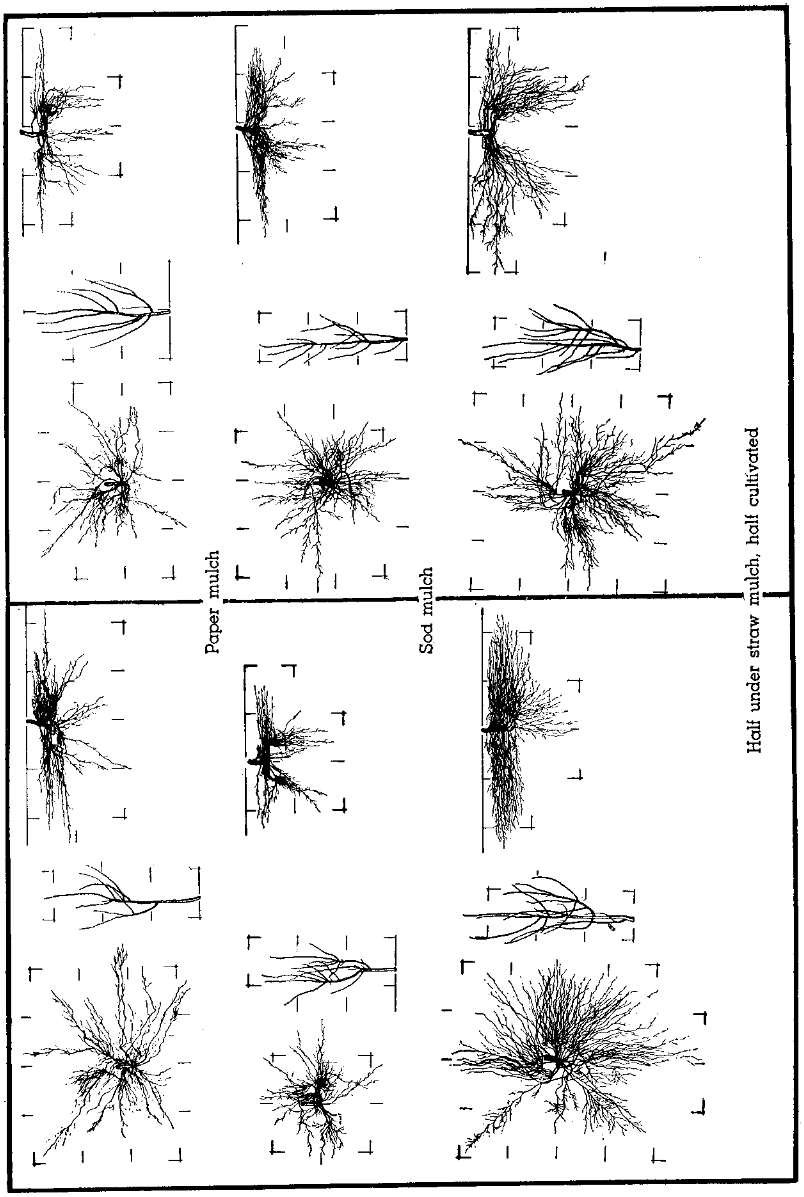

PLATE 4.—One-year-old root systems grown in clay loam soil, Lincoln, under mulch treatments. Each interval indicates two feet.

late fall and early spring and also made a slow growth throughout the winter months. This growth occurred during the time when there were no corn plants to compete for moisture. Lateral extension of tree roots in the upper two to three feet of soil was considerable during this time.

Data on soil moisture indicate that corn alone used more water than either the trees alone or the trees interplanted with corn. The drawings and Table 10 show that although root development varied but little among the several lots of trees the first season, the dwarfing effect of the corn is evident. The root systems of those trees where corn was planted 3.5 feet distant were the smallest, averaging 5 feet in depth and 6.8 feet in lateral

TABLE 10.—*Lateral spread and depth of roots after a single season of growth.*

Culture	No. trees	Lateral spread: No. roots	Lateral spread: Average	Length longest lateral root	Depth: No. roots	Depth: Average	Depth: Maximum
			Ft.	*Ft.*		*Ft.*	*Ft.*
UNION							
Cultivation only	3	57	8.3	5.7	27	6.7	8.7
Corn planted 3.5 feet from trees	3	56	6.8	4.7	29	5.0	7.0
5 feet from trees	3	59	7.4	5.4	24	5.1	6.4
7 feet from trees	2	33	8.0	5.7	16	6.2	8.0
Cultivation							
Plus ammonium sulfate	3	40	7.3	4.4	18	6.5	7.6
Plus acid phosphate	2	35	6.0	4.5	16	6.2	7.8
LINCOLN							
Cultivation	2	50	6.5	4.4	16	3.2	3.9
Straw mulch	3	67	7.0	6.0	14	2.7	4.9
Straw one side[1]	2	17	7.7	5.4	9	2.4	3.9
Cult. other side	.	38	7.5	6.0	10	1.8	3.1
Paper mulch	2	28	6.8	5.0	12	3.2	4.4
Sod mulch	2	34	5.5	4.7	10	3.0	3.7

[1] Data in this and following line represent opposite sides of trees.

spread (Plate 1). With the 5-foot spacing of corn the tree-root systems were slightly larger, averaging 5.1 feet in depth and 7.4 feet in lateral spread. The trees with corn 7 feet distant averaged 6.2 feet in depth and 8 feet in lateral spread (Plates 1 and 2). Similar measurements for cultivated trees were 6.7 and 8.3 feet respectively. Thus the 7-foot spacing of corn did not seem to disturb materially the root development of the apple tree the first year. Representative root systems from trees in each of these four lots of the corn series are shown together. The general dwarfing effect of the corn may be seen quite clearly.

The extreme depth and lateral spread of one-year-old roots were considerably greater than the averages recorded (Table 10). With corn rows spaced 3.5, 5, and 7 feet from the trees, the maximum length of apple roots toward the corn rows was, respectively, 4.7, 5.4, and 5.7 feet. The

maximum depth reached by these same trees was 7.0, 6.4, and 8.0 feet, respectively. The maximum length of lateral roots of cultivated trees was 5.7 feet; of cultivated trees fertilized with ammonium sulphate 4.4 feet; and of cultivated trees fertilized with acid phosphate 4.5 feet. The maximum depth of cultivated trees was 8.7 feet, of similar trees fertilized with ammonium sulphate 7.6 feet, and of cultivated trees fertilized with acid phosphate 7.8 feet.

The effect of nitrogen and phosphorus fertilizers upon cultivated trees is shown in Plates 2 and 3. There was no consistent change in the general character of root development of the trees due to the use of either nitrogen or phosphorus fertilizer. The trees treated with the fertilizers resembled very much the trees receiving cultivation only. The vertical roots of cultivated trees fertilized with acid phosphate reached an average depth of 6.2 feet and those of similar trees fertilized with ammonium sulphate penetrated to an average depth of 6.5 feet. Although applied with great care ammonium sulphate was injurious to some trees. Seven died before the end of the first season. No other trees died during the course of the experiment in any of the plats.

Mulched series at Lincoln.—Eleven trees were excavated the first year in the mulched series at Lincoln. Trees with a straw mulch developed more shallow and longer lateral roots than cultivated control trees (Plate 3). The average spread of lateral roots was 7.0 feet for those under straw-mulch, 6.5 feet for those under cultivation, 6.8 for paper-mulched trees (Plate 4) and 5.5 for sod-mulched trees. The average depth of rooting was 2.7 feet under straw mulch, 3.2 feet under cultivation, 3.2 feet under paper, and 3.0 feet under sod. The root systems which were half under straw and half under cultivation are shown in Plate 4. These systems showed a more shallow development under straw. The horizontal view of the root system of one tree illustrates well a tendency which was found to be common with all straw-mulched trees during the second and third year. The tendency was for the main roots under straw to be more numerous, straighter, less branched and smaller in diameter for their length than the roots of cultivated trees. Fibrous roots were more abundant under clean cultivation.

In order to determine the effect of the two soil types upon root systems of control plants, the root systems of cultivated trees at Lincoln should be observed first and then compared with those from similar trees grown on loess soil at Union. At Lincoln cultivated trees were 3.5 to 4 feet in extreme depth, and 8 to 8.8 feet in extreme lateral spread. The cultivated trees on loess had the more extensive root systems both in depth and spread, being 6.5 to 8.5 feet in extreme depth, and 9 to 11.0 feet in extreme lateral spread. Thus the depth in loess was nearly twice as great after one season of growth and the lateral spread about a foot greater on each side of the tree.

ROOT DEVELOPMENT AFTER TWO SEASONS OF GROWTH

The differences in growth of roots in the various lots of trees became more significant after two years. At Union they continued to develop vertically at a rapid rate, but less rapidly horizontally. At Lincoln, lateral development was more rapid than the vertical.

Results at Union.—Thirteen trees were excavated in the corn series after the second year of growth. The trees, being well rooted now, had a decided advantage over the corn. The data on average lateral spread and average depth of roots in Table 11 represent a large number of measurements.

In general, lateral growth of tree roots was least when corn was planted nearest the trees (Plates 5 and 6). When corn was planted 3.5 feet from the trees during two years, the average lateral spread was 8.3 feet; when five feet distant, it was 9.5 feet; and when seven feet distant, it was 10.2 feet. The inhibiting effects of the corn may be judged by comparing these averages with the average spread of 15.5 feet for trees under clean cultivation (Plate 7). Even the widest spacing dwarfed the lateral growth of tree roots somewhat the second year. The greatest reduction in lateral spread occurred below the surface two or three feet. Among all the trees in the corn series there was a marked tendency for lateral roots to turn sharply downward as they approached the drier soil under the corn. Much of the lateral growth of roots near the surface was made while corn was not competing for water.

The average depth of rooting was 11.3 feet where corn grew nearest the tree row (3.5 feet) for two consecutive years. It was 9.8 feet where corn grew farthest (7 feet) from the tree for two consecutive years and was the same as under clean cultivation. The maximum depths of rooting in the corn series the second year varied from 13 to 14.7 feet, while with cultivated trees it was 12 feet. Trees receiving ammonium sulphate had an average root depth of 7.5 feet and a spread of 13.8 feet, and those receiving phosphate had an average root depth of 9.9 feet and a spread of 15.2 feet (Plates 7 and 8).

Mulched series at Lincoln.—Eleven trees in the mulched series were excavated at Lincoln the second year. Three cultivated trees showed the smallest average lateral development of roots, 11.9 feet, and the greatest vertical growth, 6.3 feet (Plates 8 and 9). The two straw-mulched trees had the greatest average lateral spread of roots, 17.2 feet, while paper-mulched trees had an average spread of 14.0 feet. The extreme spread of lateral roots was 15.6 feet for the cultivated trees, 21.2 feet for those under the straw-mulch, and 17.0 feet for the paper-mulched trees. No sod-mulched trees were dug the second and third years.

Three trees, each of which had grown with half of the root system under straw much and half under cultivation for two years, were excavated the second year (Plate 9). The effect of the straw-mulch was apparent in these cases. The halves of the root systems under straw averaged 7.5 feet in lateral spread in contrast to an average spread of 5 feet under the cultivated halves. The average depth of rooting was 5.2 feet under the

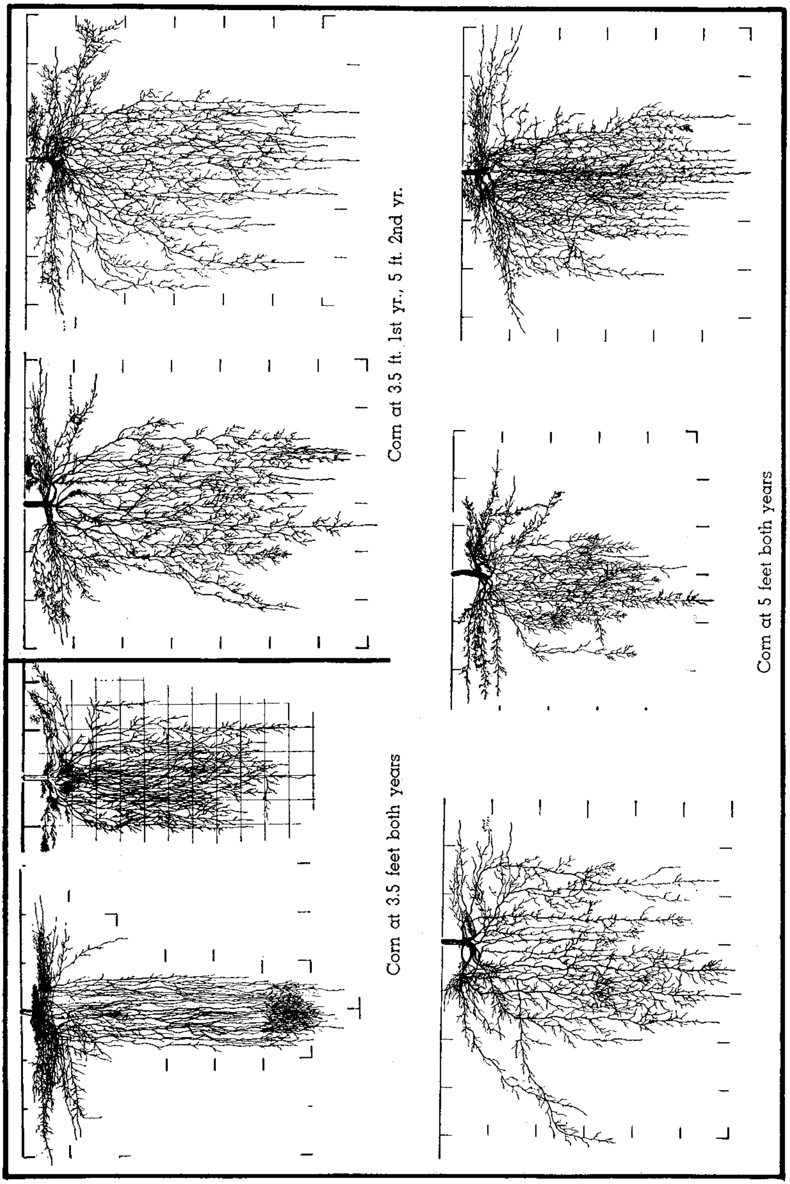

PLATE 5.—Root systems of two-year-old Delicious apple trees developed in loess soil at Union in competition with corn on both sides of the trees at the distances indicated. Each interval indicates two feet, except where lines are continuous, indicating one square foot per square.

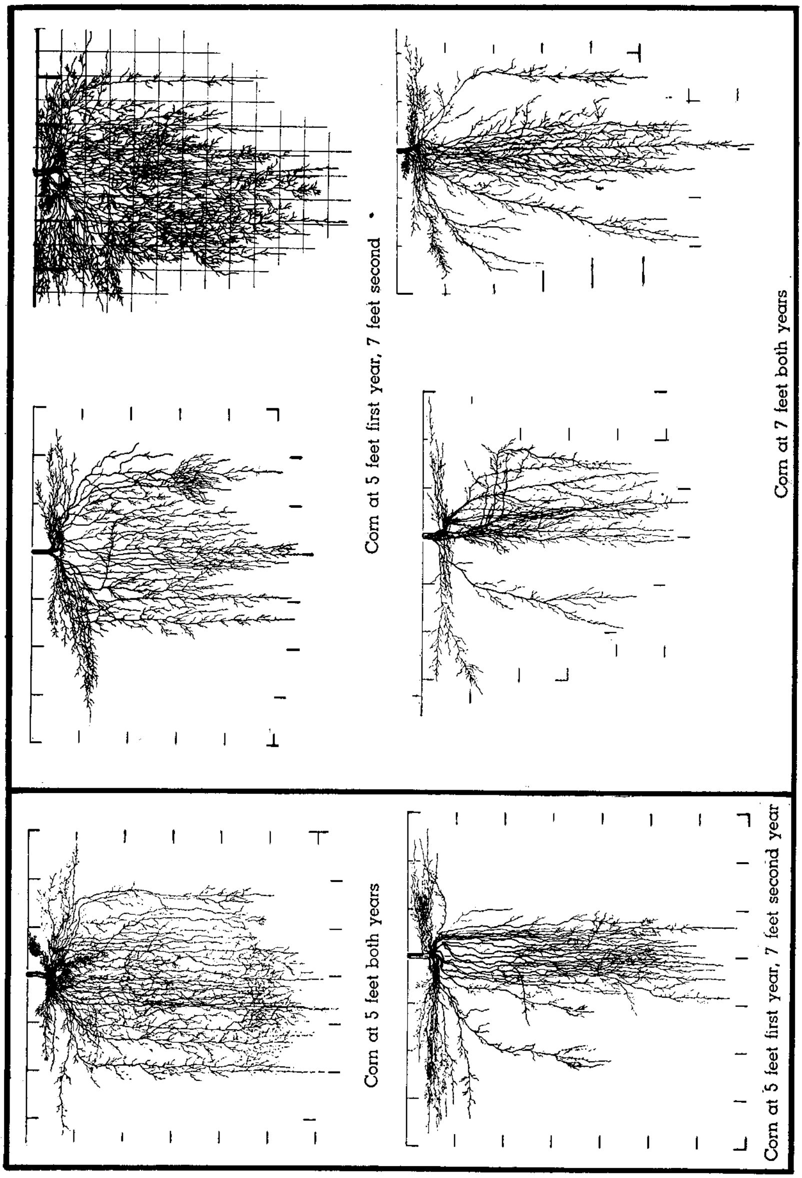

PLATE 6.—Two-year-old trees, loess soil at Union. The center root system below was injured by white grubs. A large number of vertical roots were severed about 18 inches below the surface. Each interval indicates two feet, except where lines are continuous, indicating one square foot per square.

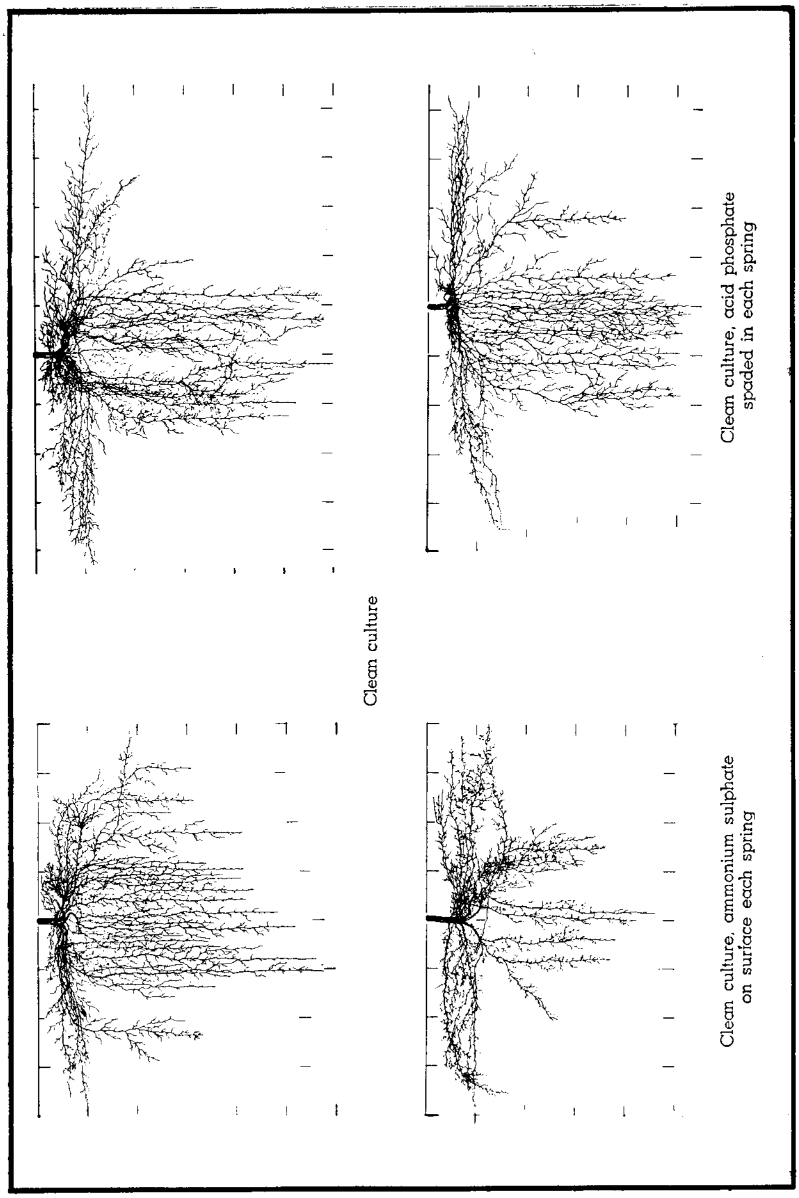

PLATE 7.—Two-year-old root systems grown in loess soil at Union under cultivation. Each interval indicates two feet.

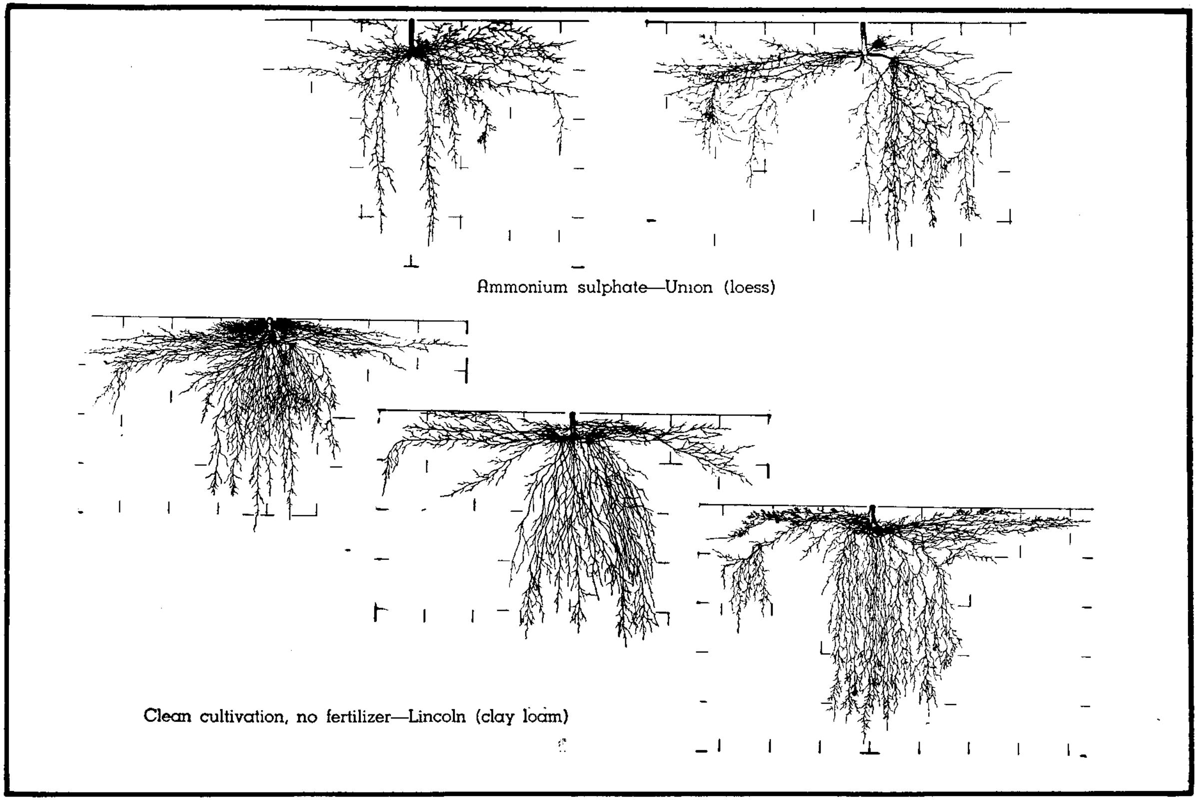

PLATE 8.—Two-year-old root systems grown under cultivation. Above in loess soil at Union; below, in clay loam at Lincoln. Upper left, ammonium sulphate was applied 6 inches below roots at transplanting and again in the second year by means of four holes 18 inches deep. Upper right, the fertilizer was applied on the surface in a circle with a three-foot radius. The three lower trees were grown under clean culture, without fertilizer. Each interval indicates two feet.

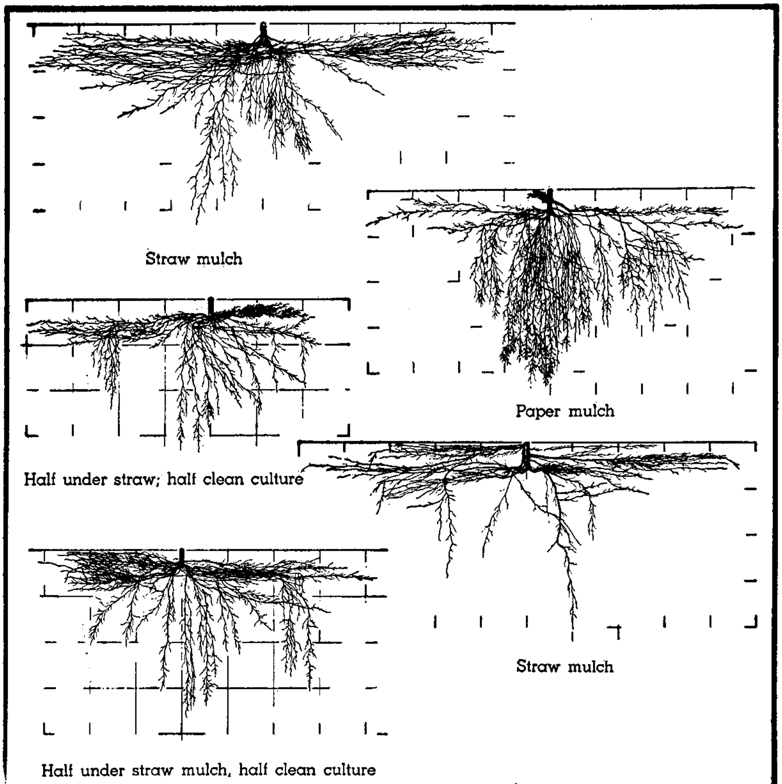

PLATE 9.—Delicious apple root systems grown two years in clay loam at Lincoln under mulch treatments as indicated above. Each interval indicates two feet.

straw and 6.1 feet under the cultivated sides of the trees. Most of the roots under straw showed a striking tendency to turn downward as they approached the margin of the semicircle of straw. The straw cover extended seven feet from the trees on one side but apparently this was not far enough to keep the roots entirely under the influence of the mulch.

The differences in soil and climatic conditions at the two stations are shown by the growth of cultivated trees. The average spread of roots was 15.5 and 11.9 feet, and the maximum spread 21.4 and 15.6 feet respectively at Union and Lincoln. The average depth of these cultivated tree roots was 9.8 and 6.3 feet, and the maximum depth 12.0 and 9.6 respectively at the two places (Table 11).

TABLE 11.—*Lateral spread and depth of roots after two years of growth.*

Culture	No. trees	Lateral spread		Length longest lateral root	Depth		
		No. roots	Average		No. roots	Aver-age	Maxi-mum
			Ft.	*Ft.*		*Ft.*	*Ft.*
				UNION			
Cultivation only	2	10	15.5	10.7	22	9.8	12.0
Corn spaced from trees							
3.5 and 3.5 feet	2	20	8.3	6.5	17	11.3	13.3
3.5 and 5 feet	2	23	7.8	7.3	19	11.8	14.2
5 and 5 feet	4	40	9.5	8.3	35	9.3	13.0
5 and 7 feet	3	29	11.2	7.6	28	10.7	13.6
7 and 7 feet	2	15	10.2	6.7	17	9.8	14.7
Cultivation							
Plus ammonium sulfate	3	17	13.8	8.4	20	7.5	9.2
Plus acid phosphate	1	9	15.2	9.2	11	9.9	10.6
				LINCOLN			
Cultivation	3	23	11.9	7.8	29	6.3	9.6
Straw mulch	2	42	17.2	10.6	21	5.4	8.6
Straw half of tree[1]	3	13	12.5	8.8	22	5.2	9.2
Cult. half of tree	3	12	12.5	7.7	22	6.1	9.7
Straw mulch 1st year cult. 2nd year	1	12	13.3	7.9	11	5.2	6.2
Cultivation 1st year, straw mulch 2nd year	1	8	19.8	8.0	5	6.8	8.7
Paper mulch	2	11	14.0	8.5	30	5.8	8.8

[1] Data in this and following line represent opposite sides of trees.

ROOT DEVELOPMENT AFTER THREE SEASONS OF GROWTH

Root development was very rapid the third season. Vertical elongation of roots again exceeded lateral spread in the loess soil, but in the mulched series at Lincoln lateral development continued at a more rapid rate than did the vertical growth. All root systems excavated the third year were so extensive that from seven to ten days were required to excavate, measure, and draw the underground parts of a single tree. A total of fifteen root systems were excavated, by the same methods employed during the second year.

Results at Union.—Nine root systems were excavated in loess soil. Two of the trees had been grown under clean cultivation, but only one tree was excavated from each of the other treatments. All of the root systems exceeded 14 feet in depth. Maximum depth was 17 feet. The average depth reached by the nine trees was 15.5 feet (Table 12).

The root system shown in Plate 10 (upper left) is from the corn series. It was grown three years with the nearest rows of corn at a distance of 3.5 feet during each year. The upper portions of the vertical roots of this tree were confined to a column of soil only about five feet in diameter. Below eight feet, the roots spread laterally under the area of soil occupied by the roots of corn. The lateral root spread near the surface was 6.5 feet

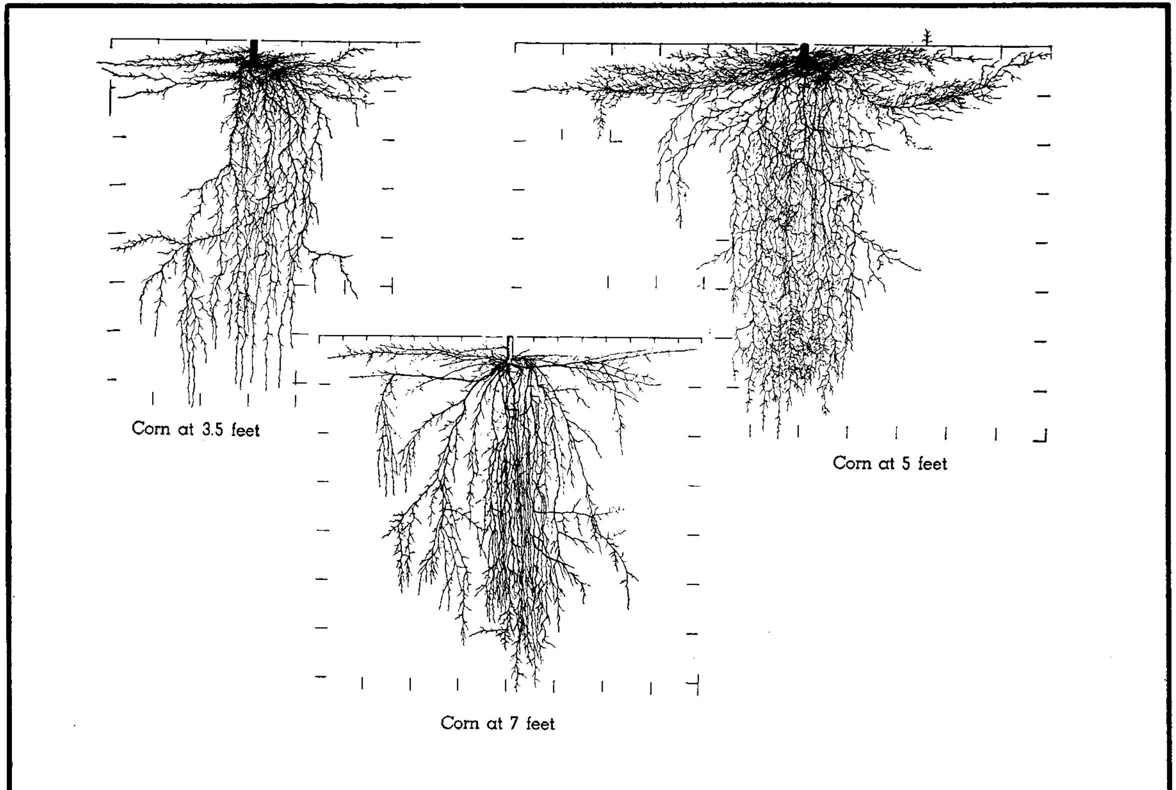

PLATE 10.—Three-year-old root systems developed in competition with corn with nearest rows at distances indicated during three seasons. Note spread of roots under corn below 8 feet, also how the roots have turned downward as they came into competition with the corn. Each interval indicates two feet.

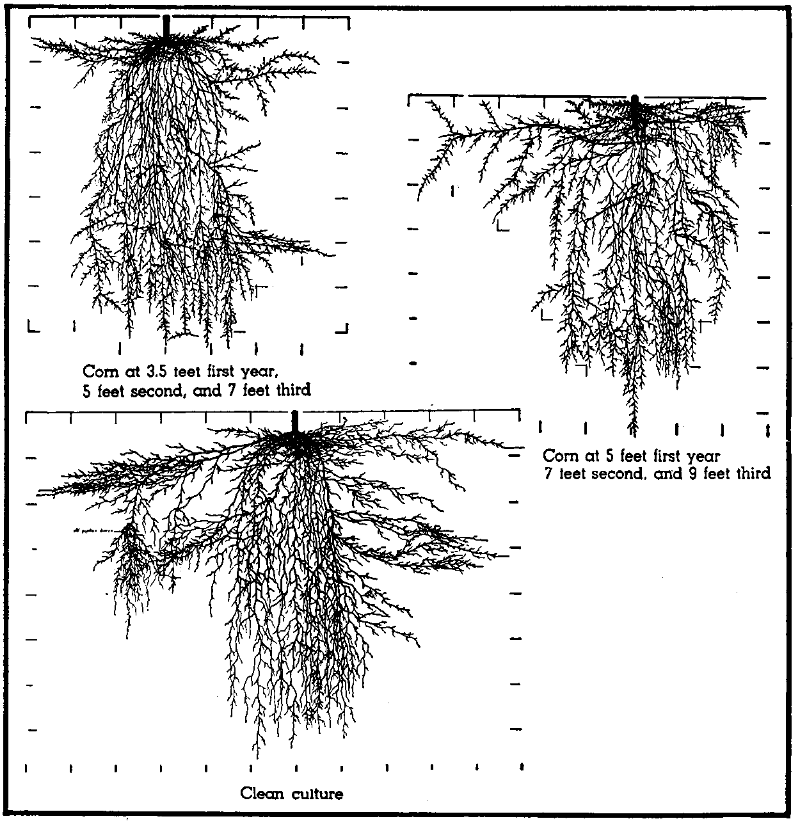

PLATE 11.—Three-year-old root systems grown in loess soil at Union. Two in competition with corn and the third under clean culture. Each interval indicates two feet.

in each direction but below eight feet it was 6 feet on one side and 4.5 feet on the other.

Plate 10 (upper right) shows a root system grown three years with the nearest rows of corn five feet distant each year. This root system was very uniform and vigorous. The lateral spread was unusual for a tree in the corn series, being nearly equal to that of cultivated trees. The vertical roots, however, were here confined to a very definite column of soil, about 5.5 feet in diameter. There was a slight tendency for the roots to spread again below eight feet.

A wide spacing of corn checked the lateral spread of tree roots considerably in their third year of growth. Plate 10 (below) is the root system of a three-year-old tree grown with corn seven feet distant for three years. The roots were, in general, spread much more widely here than with the closer plantings of corn. The roots spread horizontally from the

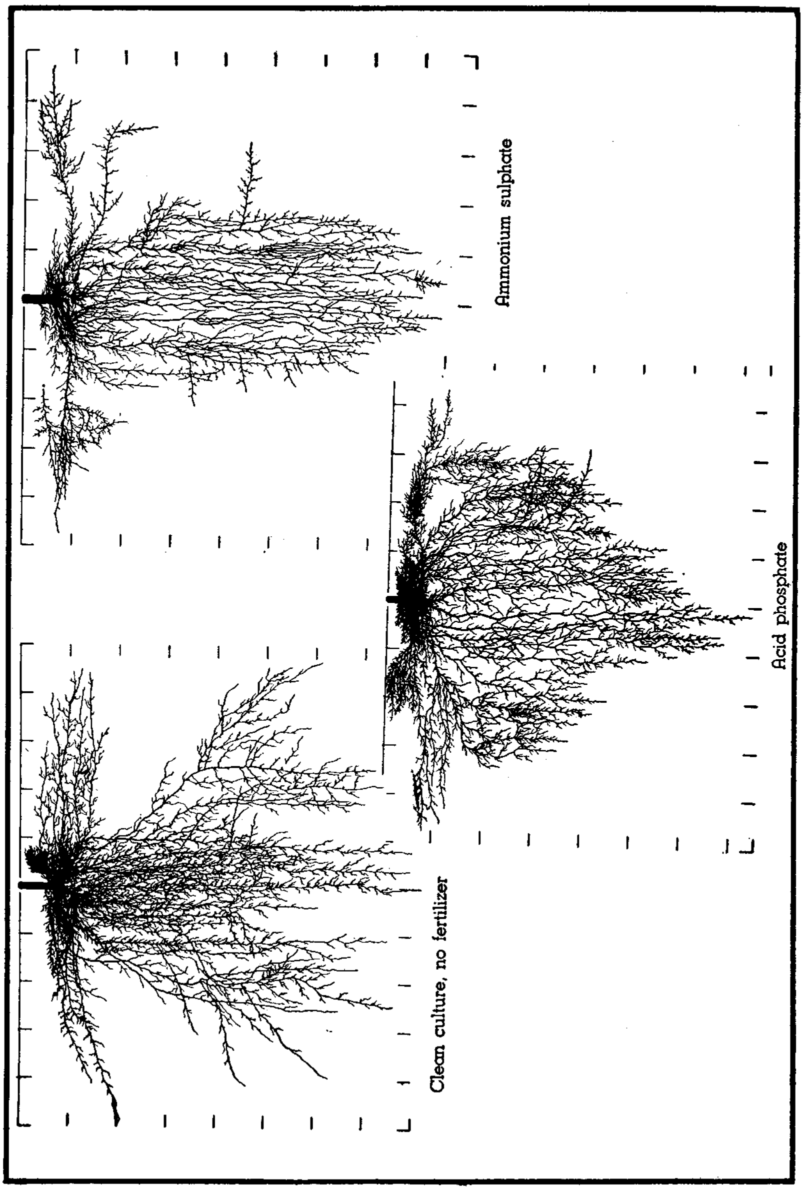

Plate 12.—Three-year-old apple root systems grown under clean culture in loess soil at Union. Upper right fertilized each spring with ammonium sulphate on surface. Lower system fertilized with acid phosphate spaded into the top soil each spring. Each interval indicates two feet.

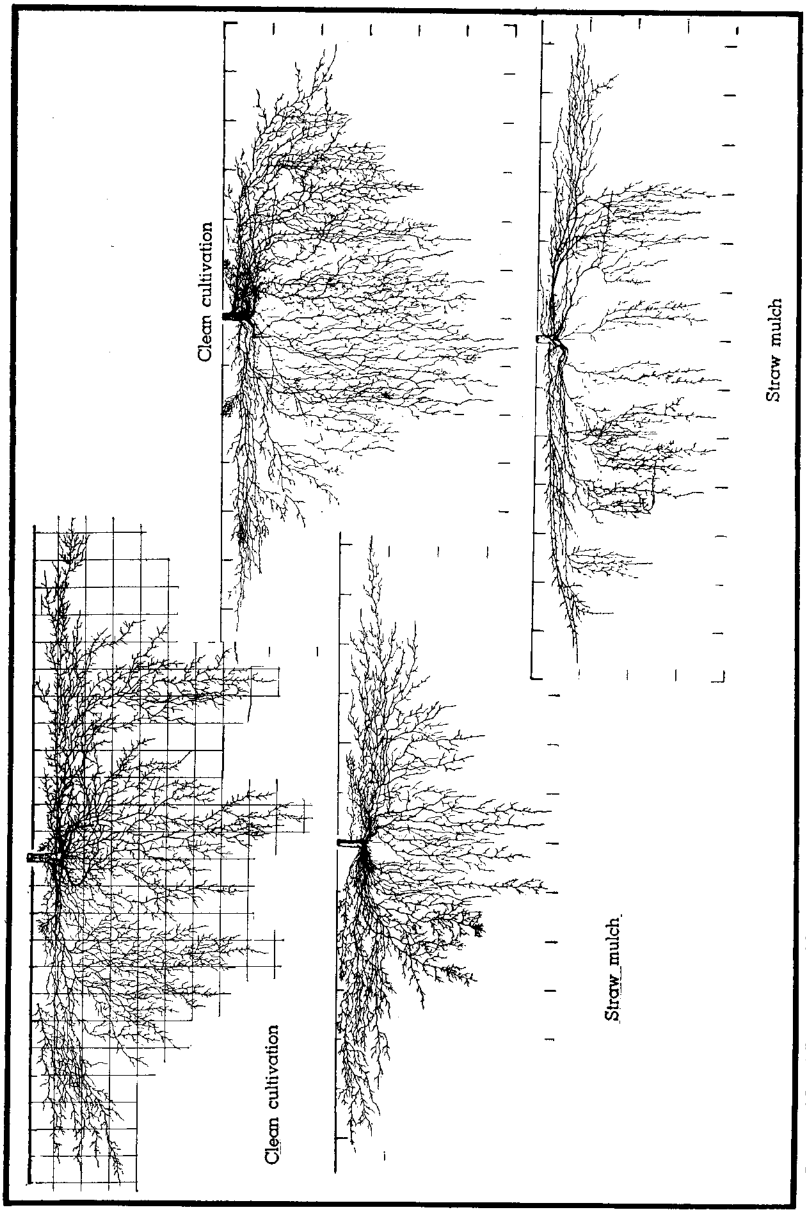

PLATE 13.—Three-year-old root systems grown in clay loam at Lincoln. Each interval indicates two feet, except where lines are continuous, each square indicating one square foot.

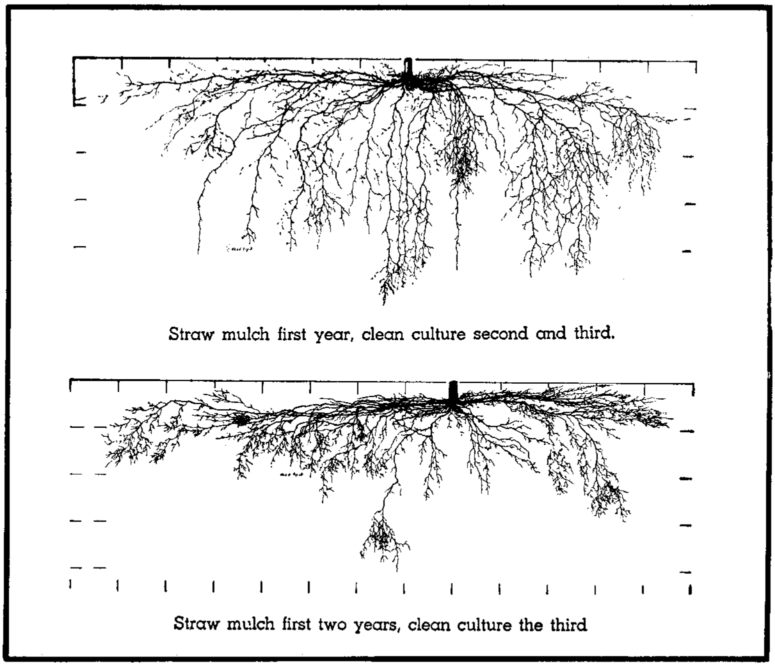

PLATE 14.—Three-year-old root systems shifted from straw mulch to clean culture in clay loam at Lincoln.

trunk five feet each way to a depth of ten feet except in the surface foot, where they spread 7.7 feet. The lateral roots showed a decided tendency to turn downward as they came into competition with the corn. The extreme depth and lateral spread of roots of this tree were 14.5 and 15.4 feet, respectively.

Plate 11 shows three-year-old root systems from the corn series where the corn rows were planted farther from the tree each succeeding year. In Plate 11 (left, above), the nearest rows of corn were planted at a distance of 3.5 feet in 1932, 5 feet in 1933, and 7 feet in 1934. This root system showed the effect of close competition with corn in early life by the restricted spread of large roots in the upper six feet of soil. However, as corn was grown farther away it spread wider by the development of laterals or by the main roots turning somewhat laterally. In Plate 11 (right) the nearest rows of corn were planted 5, 7, and 9 feet from the two sides of the tree in succeeding years. This root system resembles in many respects that in Plate 10 (below), which grew with corn at a distance of 7 feet during three successive years.

Three-year-old root systems of cultivated trees grown in loess soil are shown in Plates 11 and 12. Both of the root systems were very widespreading, not only in the upper soil but to a considerable depth as well.

One root system had a lateral spread of 9 feet on each side at a depth of 7 feet. This tree had a well defined set of vertical roots which occupied a rather distinct column of soil 6 feet in diameter to a depth of 14 feet.

TABLE 12.—*Lateral spread and depth of roots, after three years of growth.*

Culture	No. trees	Lateral spread		Length longest lateral root	Depth		
		No. roots	Average		No. roots	Average	Maximum
			Ft.	*Ft.*		*Ft.*	*Ft.*
				UNION			
Cultivation	2	10	19.2	11.6	16	14.7	16.3
Corn spaced from trees							
3.5, 3.5, and 3.5 feet	1	5	12.0	6.7	8	14.3	15.3
5, 5 and 5 feet	1	5	19.3	12.1	8	14.8	16.1
3.5, 5, and 7 feet	1	4	12.3	6.9	7	14.2	14.7
5, 7 and 9 feet	1	4	14.0	9.5	11	12.5	15.1
7, 7, and 7 feet	1	7	13.2	7.8	9	12.2	14.5
Cultivation							
Plus ammonium sulphate	1	5	17.3	9.5	6	16.1	17.0
Plus acid phosphate	1	5	17.7	9.5	6	12.4	14.7
				LINCOLN			
Clean cultivation	2	11	23.3	13.0	18	9.4	12.7
Straw mulch	2	12	23.7	13.3	16	7.2	8.7
Straw mulch 1st year, cultivation 2nd, 3rd year	1	6	21.8	14.0	10	8.9	10.5
Straw mulch 1st, 2nd year, cultivation 3rd year	1	5	20.3	14.7	13	5.5	8.2

The disturbing effect of an abandoned gopher burrow (Plate 11) is shown on the left side of this root system. The presence of fertile top soil and a greater supply of moisture probably account for abundant root development in this area. The other root system had a spread of about 17 feet at the 12-foot depth. This spread was practically the same as that in the upper three feet of soil. This wide spread of roots at great depths is the most distinct difference between the root systems of trees under clean cultivation and the root systems modified by competition with corn. The extreme depth of rooting was about the same for the clean-cultivated and intercropped trees and averaged 15.5 and 15.3 feet respectively.

Three-year-old root systems of cultivated trees which received fertilizer treatments each year are shown in Plate 12. Acid phosphate spaded into the top soil about one of these apparently did not promote root development, an effect often attributed to phosphate fertilizers. This root system was less extensive than that of any of the cultivated trees. Ammonium sulphate was spread about the other tree each spring. No effect of the nitrogen could be discerned in the development of this root system in the three-year period. Apparently nitrogen and phosphorus are not limiting factors in the development of the root systems of young trees in this section.

Mulched series at Lincoln.—Six root systems were excavated at Lincoln in the mulched series after the third year. These six trees had an average root spread of eleven feet on each side of the trunk. This spread was about two feet greater than that of the roots of cultivated trees at Union. The average depth of rooting of the six trees at Lincoln was 7.7 feet, as compared with an average of 14 feet for all trees excavated at Union the third year (Table 12).

The cultivated trees at Lincoln continued to be more deeply rooted and to have less root spread than those under straw-mulch. The root systems of cultivated trees had an average root depth of 9.4 feet and a root spread of 23.3 feet (Plates 13 and 14), while straw-mulched trees had an average root depth of 7.2 feet and a spread of 23.7 feet. The extreme depth of rooting attained by these trees was 12.7 feet under cultivation and 8.7 feet under straw, and the extreme spread of roots was 26 feet under cultivation and 26.6 under straw.

In Plate 14 are shown two root systems which were shifted from straw mulch to clean cultivation. One root system was grown under straw much the first year and under cultivation thereafter. The other was grown under straw mulch two years and under cultivation the third year. The first root system very closely resembled those that were under cultivation for the entire three years. The second root system resembles very closely those that were under straw the entire three years. There was much fine branching toward the tips of the roots, however, which is characteristic of the type of root growth found under cultivation. Apparently apple roots are easily modified to meet changing conditions.

GROWTH OF ROOT TIPS

Just back of the apex of growing roots there is rapid cell division and elongation. By increase in the size of cells in this region the root tip is forced through the soil. Soon after elongation ceases, the cortex of the root is cut off by suberization of internal tissues and by secondary growth; consequently it dies. This cortex then turns brown and decays. Rogers (31) found that usually 14 to 30 days elapsed before the white portion of apple roots began to be suberized and the cortex began to turn brown.

During the first year it was observed that young, white root tips were present during all the time excavation was in progress. This indicated that the roots were active even during the dormancy of the top of the tree. During the second year, the white portions of root tips of 313 roots were measured. The average length was 7.1 inches in October; 5 in November, 3.7 in December; 3.6 in March; 4.6 in April; and 5.8 inches in May. Root growth was rapid in late autumn, declined gradually to a minimum in midwinter, and then increased gradually during late winter and spring. It may therefore be concluded that apple roots make considerable growth while the tops are dormant. From the averages obtained it seems that main roots may elongate two to three feet during the dormancy of the top.

It was observed in December, 1933, that the root tips were most active at the lower levels in the soil, but the following spring they were making

most rapid growth near the surface. Of 146 measurements of root tips taken in April, 75 were in the upper two feet of soil and 41 were below ten feet. In the upper two feet the white tips averaged 5.5 inches in length and below ten feet, 3.3 inches.

GROWTH OF TWIGS

The total twig growth per tree, expressed in inches (Table 13) was used to measure the effect upon the top of the tree of the various cultural practices. During the first and second seasons total linear growth showed clearly the effect upon top development resulting from the different treatments. By the third season so many of the trees in each lot had been excavated and the growth of the remaining ones was so variable that these measurements did not seem significant.

TABLE 13.—*Annual growth of twigs at Lincoln and Union during the different years.*

Culture				1932		1933		1934	
				Number trees	Average growth	Number trees	Average growth	Number trees	Average growth
	1st.	*2nd.*	*3rd. yrs.*		*In.*		*In.*		*In.*
UNION									
Corn ...	3.5′	3.5′	3.5′	15	260	6	919	1	1617
Corn ...	3.5′	5′	...	..	...	6	934	.	....
Corn ...	3.5′	5′	5′	..	...	.	...	2	1092
Corn ...	5′	5′	5′	15	244	6	931	2	1376
Corn ...	5′	7′		..	...	6	876	.	....
Corn ...	5′	7′	9′	..	...	.	...	6	1567
Corn ...	7′	7′	7′	9	258	6	948	4	1243
Corn ...	7′	7′	9′	.	...	.	...	1	1286
Cultivation				9	284	6	1069	2	1177
Plus acid phosphate				9	256	6	1049	2	1188
Plus ammonium sulphate below surface				12	167	10	850	8	1069
Plus ammonium sulphate in surface				9	187	8	776	7	1219
LINCOLN									
Straw mulch				12	424	6	1586	3	2108
Straw mulch under half of tree ...				9	350	7	1402	3	1370
Cultivated				9	331	6	1369	3	1466
Paper mulch				6	284	4	1054	2	1162
Sod mulch				6	266	4	633	2	1435

In the mulched series at Lincoln, average twig growth for the first year was proportional, in general, to average root growth. It was 266 inches for sod mulch, 284 for paper mulch, 331 for clean cultivation, 350 with half straw mulch and half cultivation, and 424 inches with straw mulch alone.

The trees on loess soil did not make as much twig growth as did those at Lincoln. Trees under clean cultivation made an average twig

growth the first year of 284 inches at Union and 331 inches at Lincoln. The trees in the corn series produced about the same amount of twig growth whether corn was planted near the trees or farther away.

During the second growing season the differences in twig growth were still more pronounced in the mulched series. The average increase per tree was 633, 1,054, 1,369, 1,402, and 1,586 inches for the trees grown under sod mulch, paper mulch, clean cultivation, half straw and half cultivation, and straw mulch, respectively. The total twig length, including that of the previous season for the two extremes, was 899 inches for trees under sod mulch and 2,010 inches for trees under straw mulch. Total twig growth of cultivated trees for the two seasons averaged 1,700 inches. Trees at Union under clean cultivation made an average growth of 1,069 inches and those at Lincoln 1,369 inches. During the third year trees under clean cultivation averaged 1,177 inches of twig growth at Union and 1,466 inches at Lincoln.

The average height of trees, with one exception, varied in much the same manner as did the growth of twigs (Table 14). In the corn series the height of trees was greatest where corn was grown nearest the trees the second and third seasons. Apparently decreased light resulted in the twigs growing in a more nearly vertical direction. The tallest group of trees, those in the corn series, had an average height of 8 feet the third

TABLE 14.—*Average height of experimental trees after each of three seasons of growth.*

Culture				1932	1933	1934
	1st.	*2nd.*	*3rd. yr.*	*Ft.*	*Ft.*	*Ft.*
UNION						
Corn ...	3.5′	3.5′	3.5′	5.5	7.3	8.5
Corn ...	3.5′	5′	5′	..	7.1	8.2
Corn ...	3.5′	5′	7′	..	6.9	8.0
Corn ...	5′	5′	5′	5.9	6.8	7.8
Corn ...	5′	7′	9′		7.2	7.5
Corn ...	7′	7′	7′	5.8	7.0	8.0
Average				5.7	7.0	8.0
Cultivation				5.8	6.8	7.3
Plus ammonium sulphate below				4.4	6.7	7.1
Plus ammonium sulphate on surface ..				5.6	7.1	7.3
Plus acid phosphate.................				5.0	6.8	7.2
Average				5.5	6.9	7.2
LINCOLN						
Cultivation				6.1		7.2
Straw mulch				5.6		7.7
Half straw, half cultivation............				5.0		7.7
Paper mulch.........................				5.3		6.9
Sod mulch...........................				4.8		7.1
Average				5.3		7.1

year but the maximum root depth of these trees was just twice as great. The average height of all trees measured at Lincoln the third season was 7.1 feet, but their average maximum depth was 10 feet.

DISCUSSION

The root systems of young Delicious apple trees transplanted from the nursery to the orchards were plastic and readily modified by changes in the soil environment. Intercropping with corn and consequent competition for moisture in the first few feet of soil resulted in a marked vertical development of the tree roots. The straw mulch conserved the water near the surface and this resulted in a remarkable lateral development of tree root systems when contrasted with their growth under clean cultivation. When these modifying influences were removed, the root systems developed in the usual manner and approached the generalized type. Whatever the course of development, it seems that the root system of the mature tree will continue where possible to extend indefinitely into new areas of soil where more moisture is available for their use.

In the corn series the horizontal tree roots changed their course downward when they came into the areas where soil moisture was being depleted by the corn roots. This change in direction of growth was a striking feature of the tree-root development. Where corn grew near the trees the first and second seasons nearly all of the tree roots grew vertically downward. Since these roots turned downward early in life, and lateral spread was limited, a larger number of them reached a greater depth than was the case under any other environmental condition. Below 8 feet the roots spread laterally under the area occupied by the corn. Thus as Kvarazkhelia (20) has indicated, apple roots extend toward the most favorable environment. Because of such adaptations these young trees seemed able to secure enough moisture to insure a top growth nearly equal to that of trees under clean cultivation.

In the mulched series all of the root systems had a pronounced shallow, lateral development. This was especially noticeable under the straw mulch. Straw caused more of the rainfall to be absorbed and also effectively decreased evaporation of water from the surface of the soil. This made available a larger amount of moisture in the upper soil and doubtless contributed to the more shallow rooting and to the relatively greater top growth of trees grown under the straw mulch. The mulch seemed to change the physical structure of the soil also, as was indicated by the study of percolation. Because of the impervious nature of the zone of concentration at 18 to 36 inches of depth, there was, at times, a water-logged condition of the soil under the straw. Stevenson (36) in a study of orchard soils in Oregon, has pointed out that only soils with 10 per cent or more of pore space in addition to that occupied by water at field capacity, are satisfactory for the growth of apple trees.

The main roots developed under straw were more numerous, smaller in diameter in proportion to length, had less fibrous branches, and were straighter than roots of trees under clean cultivation. Both the root sys-

tems and tops of trees under sod mulch were dwarfed in comparison with trees under cultivation. Under paper mulch, dwarfing was present but to a less degree. These findings agree with those of Clements, Weaver, and Hanson (8) with deciduous tree seedlings, who found that the roots were greatly reduced by different degrees of competition with grasses.

Soil moisture was the most important edaphic factor in determining the type of development made by the young apple trees. Holch (16) has shown that the form of the root system is correlated with the water supply of the soil. The severe drouth of 1932 doubtless made soil moisture a more important factor than usual in the growth of roots and tops. Baker (4) has indicated that a tree is able to adjust itself to its changing environment by the way in which it utilizes its food reserves in new growth. This has seemed to be true of the trees in this experiment, in their adjustment to the soil moisture supply, as evidenced by the development of a larger root system and smaller top at Union than at Lincoln. The three seasons of 1932, 1933, and 1934 were all deficient in annual precipitation at Union, while at Lincoln only the season of 1934 was greatly deficient. Soil-moisture data show that during the first and the second growing seasons moisture was more abundant in the shallower soils at Lincoln than at Union. The roots of the trees at Lincoln were able to supply the top with an abundance of moisture without expending so much of the tree's energy in root extension. More food reserves were then available for growth of tops. At Union somewhat the reverse conditions seemed true.

The differences in the physical character of the two soil types doubtless had considerable effect upon the type of rooting. Studies on percolation showed that the soil at Lincoln is much less permeable to moisture than the loess. A slow percolation rate causes free water to be held much longer near the surface and this may account in part for the more shallow rooting of the trees at Lincoln. Roots could not penetrate the soil at Lincoln so readily as they could the more mellow loess soil. The roots of the Lincoln trees were decidedly more kinked and curved and followed more sinuous courses than those of trees growing in loess. Thus with an expenditure of the same amount of energy roots would extend farther in loess soil.

Nitrogen and phosphorus did not seem to be at all limiting to the growth of either roots or tops of cultivated trees in loess soil. Fertilizers may be of more benefit to young trees in seasons of greater rainfall, since the full use of soil nutrients is dependent upon available water.

One of the most significant things revealed by this investigation has been the exceedingly rapid rate of root development of young apple trees. During the first season the maximum spread of roots was 11.3 feet at Union under cultivation and 12 feet at Lincoln under straw mulch. The maximum depth of rooting was 8.0 feet at Union and 4.9 feet at Lincoln. The maximum growth of vertical and lateral roots of cultivated trees was 8.7 feet and 5.7 feet at Union, and 3.9 feet and 4.4 feet at Lincoln. The average vertical growth was about 25 per cent faster than lateral growth at Union, while at Lincoln lateral growth was slightly faster than vertical growth during this first year.

The second year the maximum root spread had reached 21.2 feet at Union and 21.4 feet at Lincoln, under cultivation and straw mulch respectively at the two stations. The maximum root depth was 14.7 feet at Union in the wide spacing of corn and 9.7 feet at Lincoln under cultivation. Average vertical growth under cultivation during the two years was about 25 per cent faster than lateral growth in loess soil and was about 7 per cent faster than lateral growth in clay loam soil.

The third year the maximum root spread had reached 24.2 feet at Union and 29.3 feet at Lincoln, and the maximum root depth was 17.0 feet and 12.7 feet respectively. Cultivated trees made vertical growth over 50 per cent faster than lateral growth in loess soil during the three year period, while at Lincoln in clay loam soil lateral growth was 24 per cent faster than vertical. The underground development greatly exceeded the lateral spread of tops, which was about 3 feet, and the height of the trees, which was 7 to 8 feet.

A tree of given age which most thoroughly occupies the largest volume of soil will be the one best fitted to withstand adverse conditions. Therefore the most nearly ideal root systems were developed at both stations under cultivation. Since straw mulching of young trees causes the main roots to develop near the surface it seems that straw should not be applied until the trees are at least two years old. By that time the main roots would be distributed deeply, and would be less subject to injury from severe cold, rodents, and cultivation, should cultivation be resumed later. Likewise in shallow soils, competition with corn or other interplanted crops would prove more injurious to the development of the tree root system, than in deep loess soil.

In regions of limited rainfall, as in eastern Nebraska, it may be concluded that in developing young orchards, corn should not be planted near enough to the trees to interfere greatly with the normal development of the root system. This study indicates that the first row of corn should not be nearer than five feet the year the trees are transplanted. During the second and third years the corn should not be closer than 7 feet. If the same rate of tree root growth continues in succeeding years it seems that during the fourth and fifth seasons of growth the first corn row should be at least 10 feet from the tree row. If the tree rows are spaced the usual 36 feet apart, eight rows of corn may be planted between the trees the first year, six rows the second and third years, but only four the fourth and fifth years. After five years no corn should be grown in the orchard.

The rate of root growth observed in this experiment, in connection with deep-soil moisture studies, indicates that apple trees grown in eastern Nebraska should be spaced much farther apart than has been the practice in the past. Wiggans and Yocum (55) have excavated the roots of mature apple trees at both Union and Lincoln. Jonathan trees spaced 30 by 33 feet in loess soil had in 17 years sufficient root spread to overlap in all directions and had penetrated to a depth of 30 to 35 feet, this depth being limited apparently by an impenetrable layer of shale. Practically every cubic foot of soil was occupied by roots to this depth. Jonathan trees spaced

33 by 33 feet apart at Lincoln, when 25 years old had reached a depth of 28 feet. Here a layer of pure sand checked their development. These findings indicate that large, vigorous varieties should be spaced as much as 40 feet apart without fillers or interplants of other fruit trees.

The results of this investigation indicate that great care should be exercised in the choice of an orchard soil and site to insure an ample supply of subsoil moisture to support the trees over a long period of years. In regions of limited rainfall the deep porous soils like the loess are best. The orchard site should be such that a maximum amount of annual rainfall can be absorbed and stored. It is doubtful if in eastern Nebraska there is sufficient rainfall to meet the needs of a mature apple orchard, except in the most humid seasons and in the most favorable locations. In drier seasons and on poorer soil and sites, the moisture stored through decades is used up more rapidly. No doubt the exhaustion of this subsoil moisture is the chief factor which determines the length of life of orchards in this territory.

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